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HEADQUARTERS
AIR FORCE SPECIAL WEAPONS CENTER
AIR FORCE SYSTEMS COMMAND
KIRTLAND AIR FORCE BASE, NEW MEXICO

Final Report

STUDY AND TESTING OF
RADIO FREQUENCY INSENSITIVE
ELECTROEXPLOSIVE MATCHES (SQUIBS)

October 1961

American Machine & Foundry Company
Alexandria Division
Alexandria, Virginia

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American Machine & Foundry Company
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Development Directorate
AIR FORCE SPECIAL WEAPONS CENTER
Air Force Systems Command
Kirtland Air Force Base
New Mexico

Approved:

M. E. SORTE
Colonel USAF
Director, Development Directorate

Project 5791
Task 579111
Contract AF 29(601)-2769

ABSTRACT

The USAF is endeavoring to significantly reduce the hazards associated with the inadvertent initiation of electroexplosive devices by electromagnetic fields.

A small attenuator or filter with high insertion loss and/or mismatch characteristics, preferably integral with the electroexplosive device, is considered the device which would best satisfy the existing and projected needs and objectives of the Air Force.

High-dielectric constant capacitance units used as a shunt across squib bridgewires are thoroughly investigated over a frequency range of approximately 100 kilocycles to 10,500 megacycles.

The results of laboratory work and theoretical considerations are suitably reported. The feasibility of employing such units is considered reasonably good.

PUBLICATION REVIEW

This report has been reviewed and is approved.

John J. Dishuck

JOHN J. DISHUCK
Colonel USAF
Deputy Chief of Staff for Operations

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SUMMARY

Authority

This report is the final report by the Alexandria Division of the American Machine & Foundry Company under Contract Number AF 29(601) -2769 sponsored by the Air Force Special Weapons Center, Kirtland AFB, New Mexico. The period covered by the report is the entire contract period from 2 May 1960 to 30 September 1961.

Objective

The objective of the program reported herein was to determine the feasibility of fabricating radio-frequency insensitive electroexplosive matches from combinations of simple circuit elements. Stated more simply the objective was to investigate the feasibility of fabricating a simple and compact device which would afford protection to a squib against accidental detonation by radio frequency influence. For example, such accidental detonation might occur, in the case of an unprotected squib, if the radio frequency current flowing through the bridge wire produces sufficient heating effect to ignite the explosive bead mix. Such accidental detonation might also occur, in an inadequately protected squib, as a result of heat generated elsewhere and conducted to the bead mix.

Approach

In the course of this program the approach given primary attention involved the use of a high-dielectric-constant capacitance unit connected as a shunt across the squib bridge wires. This approach cannot be described as use of a simple conventional by-pass capacitive reactance. Rather, the approach takes advantage of the reactance-alternating nature of certain types of capacitance units. Thus, the unit behaves as a capacitive reactance over one range of frequencies, as an inductive reactance over a succeeding range of frequencies, and as a virtual short circuit in transition regions. A variety of ceramic capacitance units were studied and may be classified into two general categories. The first category is characterized by very high dielectric constant (specific inductive capacity of the order of 100,000); high dissipation factor; and extremely low voltage rating. The second category is characterized by moderately high dielectric constant (specific inductive capacity from 2,500 to 12,500); low dissipation factor; and substantial voltage rating. The second category is further classified according to method of fabrication whether by extrusion process or by thin film techniques.

While primary attention was given to the use of the shunt reactance, consideration was also given to the use, as a supplemental protective device, of broadband radio-frequency absorbers, (2).

Guidance

The program involved the use of both analytical and experimental techniques. Guidance furnished by the sponsor established certain criteria for the program such as:

a. The range of frequencies to be investigated was specified as 400 cps to 11, 000 mcps.

b. Signal sources used for obtaining test data would be capable of a minimum power output of 50 watts.

c. Dimensions and other physical properties were specified for laboratory model squibs to be built and tested.

Supporting Tasks

In order to accomplish the primary objective of the program it became necessary to execute several supporting efforts as follows:

a. It was necessary to devise means of instrumentation to obtain the required data and to devise means for presentation of data to best indicate the degree of insensitization achieved over the specified frequency range. The instrumentation used consisted chiefly of coupled circuits and oscillographic or diode-detector actuated indicators. The data are presented in several ways viz.:

(1) As current protection ratio achieved plotted against frequency.

(2) As Histograms.

(3) As impedance plots using Smith Charts.

(4) As plots of voltage standing wave ratio versus frequency.

b. It was necessary to analyze the transient heating of bridge wires and to correlate such heating to the ignition properties of bead mixes. In order to fabricate laboratory model squibs for test, an analysis was made of the short-time heating of several sizes of resistance wire by various levels of current and the calculated findings were adapted to the detonating temperatures and ignition times of two bead mixes.

c. It was necessary to determine the effect of the radio-frequency insensitization element on the normal or intentional squib firing circuit. The specific requirement in this case was to determine what time delay in the intentional firing circuit is caused by the shunting capacitance unit. This time-delay was calculated analytically and the results are in agreement with oscillatory-case measurements made by R. F. Wood of the Franklin Institute.

Findings

While the program produced a voluminous amount of data on capacitance units, squib components, circuit behavior at various frequencies and general squib design, the primary findings can be summarized as follows:

a. Tests involving both squib simulating set-ups and laboratory model squibs indicate that insensitization at frequencies below 200 KC, with currently available materials and with the techniques used in this program, does not appear practicable. Further research is required to extend the protection to this range of frequencies.

b. Simple and compact laboratory squib configurations, utilizing reactance units alone, offer good protection against radio-frequency influences over a very wide range of frequencies. Typical decibel-expressed current and power protection ratios obtainable with a single device are as follows:

   (1) below 200 KC protection is less than 15 db to zero.

   (2) from 200 KC to 50 mc - protection varies in the general range from 15 db to 50 db.

   (3) from 50 mc to 1000 mc - protection varies in the range from 17 db to 10 db.

   (4) from 1000 mc to 11 Kmc - nominally 15 db with a few very narrow frequency bands where the ratio drops to values below 10 db.

c. The greatest degree of protection afforded by the laboratory models tested, using reactive components alone, occurs over the range of frequencies from 500 KC to 10 mc.

d. The use of reactive elements for insensitization in the configuration fabricated and tested will not adversely affect the normal or intentional firing circuit. The delay time is, in fact, negligible.

e. Capacitors of the first category (high dielectric constant, high dissipation factor, and low voltage rating) proved unsatisfactory primarily due to voltage breakdown problems. Capacitors of the second category proved feasible over a wide range of frequencies. Both extruded types and thin film types may be used.

f. Current protection ratios may be raised appreciably at frequencies above 500 mc by use of a broadband radio-frequency energy absorber on a supplementary basis.

Conclusions

It is concluded that:

a. The concept of using capacitance elements in shunt with squib bridge wires to afford radio-frequency protection over a very wide frequency range is indeed feasible. Further, such units may be fabricated from simple circuit elements and may be compactly packaged.

b. The use of reactive radio-frequency insensitization units as tested in this program does not adversely affect the firing circuit insofar as delay time is concerned.

c. While the radio-frequency absorber devices tested seem to offer negligible protection at frequencies below 500 mcps, the use of such devices in conjunction with a reactive unit will materially improve the protection ratio at frequencies above 500 mcps.

d. The results of this program promise a solution to the difficult problem of protection of electroexplosive devices from radio-frequency detonations. Continued research and development based on this approach will probably produce effective devices for numerous specific applications.

I. INTRODUCTION

Within the Military Services numerous weapons systems are now deployed or planned for deployment which utilize electroexplosive matches for initiation of explosive trains, for the ignition of rocket propellants, for actuation of explosive switches, and for other similar applications. These various systems are expected to perform satisfactorily under conditions where the electromagnetic radiation environment, due to both military and civilian transmitters, may be quite dense. Further, the present trend is toward use of higher and higher transmitter power in many communications and radar applications. Thus, the possibility exists that accidental or unintentional actuations of electroexplosive devices may occur due to radio frequency influences.

On 2 May 1960 the Alexandria Division of the American Machine & Foundry Company entered into a contract, sponsored by the Air Force Special Weapons Center at Kirtland AFB, New Mexico, for conduct of an investigative program aimed at a solution to this problem. The objective of this program was to determine the feasibility of fabricating a compact device from simple circuit elements which would provide protection against accidental detonation over a wide range of frequencies.

The basic philosophy governing the AMF Approach is discussed in some detail in Section II of this report. Essentially, the technique is to shunt the bridge wire with a reactive unit which diverts alternating current from the bridge wire over a wide range of frequencies. Since the shunting unit is reactive it does not dissipate appreciable energy to be manifested as heat within the squib casing. Also, line to load impedance mismatch results in power wave reflections. The overall result is that the preponderance of radio frequency energy induced into the system is ultimately dissipated in the external leads and not in the squib. The effort in this program was addressed to the protection of units utilizing bridge wires with resistance of the order of ten ohms or greater.

The key to the fabrication of effective protective units is in the materials and the configuration of the capacitance units used. The materials aspect of the program therefore required extensive effort. In this connection, the supporting efforts of the American Lava Corporation of Chattanooga, Tennessee and the Erie Resistor Corporation of State College, Pennsylvania are gratefully acknowledged.

During this program a voluminous amount of data was generated pertinent portions of which are presented in the remainder of the report. It is considered that the program was successful and that the feasibility of the technique has been demonstrated.

The contract requires that the Contractor submit drawings and specifications defining the laboratory model squib assembly that was tested. This information is contained in Appendix F to this report.

With the cooperation of the Franklin Institute of Philadelphia, Pa. consideration was given to the possibility of utilizing a broad band radio frequency absorber as a supplementary protection device. This work is described in Section VII of this report.

II. PHILOSOPHY

From rather lengthy analysis of the problem of providing protection of simple form to electroexplosive matches from high frequency current influences it was determined that the approach holding most promise was utilization of circuit elements whose nature is predominantly reactive. Underlying that analysis was perception of two, separate and distinct points in the problem, viz.: precluding the possibility, on the one hand, of flow through the bridge wire of an a-c current capable of igniting the flash mixture; and preventing, on the other hand, of development of sufficient heat elsewhere in the match so that fulmination of either the flash mixture or the included explosive could occur indirectly. Analysis of the first-mentioned aspect of the problem indicates that results of practical value may be obtained through use of the current diverting qualities of reactive elements together with the power wave reflection properties thereof. Views on the second aspect are essentially an acknowledgment of the non-dissipative nature of reactive elements, and, therefore, of the improbability that appreciable heat may be produced thereby. A complementary part of the philosophy is utilization of transmission lines to squibs as the stray power consuming and dissipating agents (6). In short, the aggregate of views is to exclude spurious power from the squibs, and cause it to be dissipated in the transmission line.

A better comprehension of this philosophy may be acquired perhaps by first reviewing events that may be shown to take place in a capacitance-unit-protected squib when exposed to signal frequencies ranging from 400.0 cps to 100.0 mc. For frequencies below a few magacycles the assumed high capacitance condenser, because of its low reactance, would divert from the bridge wire branch an appreciable fraction of the total current supplied to the squib. In this case the condenser, obviously, would be performing a conventional, by-pass service. As higher signal frequencies come into play ordinarily frequencies between 1.0 mc and 10.0 mc, the condenser would exhibit series resonant circuit characteristics. Here the current diverting property of the condenser, if of the type envisaged for application to squibs, should be appreciably enhanced because the series resistive component of the capacitor impedance would be extremely small. Continuing, frequencies above resonance cause the capacitor to behave more and more like an inductive reactance. Despite this property change the current diverting action persists though in accordance with a different law: Henceforth, the capacitance branch acts as an inductively reactive shunt. Contributing somewhat to the success of the branch operation thus is the fact that at approximately the same time that the capacitor assumes inductive properties, the bridge wire loop does likewise, it, however, making a gradual transition from a resistance. With the characteristic changes which occur at frequencies above the capacitance branch resonant frequency there is necessarily a decrease in the effectiveness of this branch to divert current. Ultimately, of course, as the capacitance and bridge wire branches behave as almost wholly inductive reactances, the current division

between the two approaches an inverse proportion to the respective branch reactance values. It follows that a fairly reasonable shunting of current through the capacitance branch may still occur if its inductive reactance is rendered small relative to that of the bridge wire. All of the changes just described, incidentally, are portrayed in the approximate equivalent circuits depicted in Fig. 1.

At frequencies well beyond those considered, as, for example, those ranging from 100.0 mc to 1000.0 mc, impedances of both the capacitance unit branch and the bridge wire loop retain the largely inductive character they assumed earlier. Loci of the impedances of bridge wires of two different lengths, of a capacitance unit, and a paralleled combination of the two, which traces are representative of those shown forth by the elements under comment in the 300.0 mc - 1000.0 mc range, are provided for illustrative purposes on the Smith charts (7) (8) comprising Figs. (2), (3), (4) and (5). Numerical values of impedances associated with the specific points plotted in the charts are listed in accompanying Tables I, II, III and IV.

The technique of using reactive elements to protect squibs against intrusive radio-frequency influences, heretofore taken up over a rather limited frequency range, admits actually of qualified extension to cases where ultra-high and microwave frequencies come into play. At these latter frequencies the view extension must comprehend the changing electrical character of both the protective unit and the bridge wire, and some broadened circuit concepts. As to the first of these points the extension of views must take into account the fact that squib elements will not remain possessed indefinitely of the simple attribute of reactance, ascribed somewhat loosely to them in the very high frequency range, but will reflect also energy absorptive properties. With regard to the second point, the depiction used earlier of squib protection stemming from current diversion through a protective reactive element requires superseding by the concept of protection being realized through certain mismatches of load and power system impedances, and consequent power wave reflections.

Just what is meant by the protective process outlined may be inferred from consideration of the following expression (9) for the power delivered to a load over a lossless transmission line under conditions where the load and line impedances are mismatched:

$$W = \frac{V_L^2}{p Z_o} \left\{ 1 - \left[\frac{1}{p^2} - 1 \right] \sin^2 \beta X \right\} \qquad (2.1)$$

In this equation

p = Voltage standing wave ratio.

$$p = \frac{E_{max}}{E_{min}} = \frac{1 + |\Gamma|}{1 - |\Gamma|} \qquad (2.2)$$

Γ = Reflection coefficient

$$= \frac{Z_L - Z_o}{Z_L + Z_o} \qquad (2.3)$$

β = Phase constant.

$$= \frac{2\pi}{\lambda} \qquad (2.4)$$

V_L = Voltage (RMS Volts) between load terminals.

Z_L = Load impedance (Ohms).

Z_o = Characteristic impedance of the transmission line (Ohms).

λ = Wavelength of current and voltage propagations (Meters).

X = Distance from the load to the nearest voltage maximum (Meters).

Effectively, the given power expression may be construed to state that if the voltage across the load (squib) impedance may be made small and if a high impedance mismatch is brought about, i.e., a high voltage standing wave ratio created; or, alternatively, if the load impedance be extremely reactive, then the power consumed by the load may be below squib detonating levels.

The varying nature of the protective reactance unit, described, in part, in the discourse of events in the 1.0 mc - 10.0 mc frequency range, where a transition from a capacitive reactance to an inductive reactance took place, will be manifest again in the ultra-high or microwave frequency range. There the unit will reassume capacitive reactance properties. If this alternation occurs while unit reactance values are large and the unit resistance value is near zero protection would still be afforded to a squib. In the event the unit resistance value were moderate, however, a fairly good match of load and power system impedances could occur. Under such condition, obviously, the squib would be without protection. Uncertainties of this kind can be resolved only by conclusive test results from representative squibs, or they can be eliminated by supplementing the protective reactance units with other forms of protection.

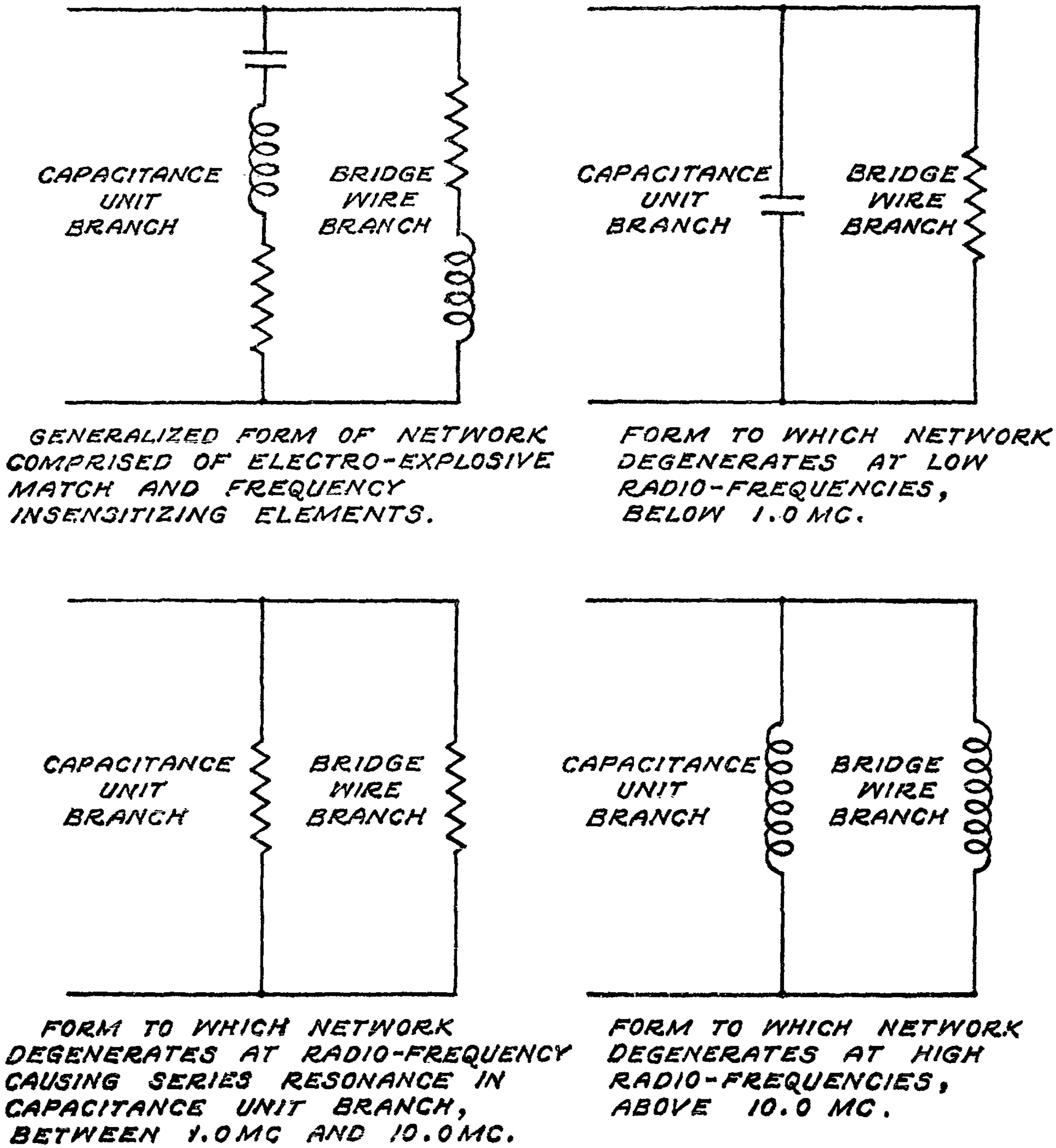


Fig. 1 - Apparent Three-Mode Operation of Capacitance Unit and Bridge Wire Arms With Frequency

Impedance Measurements at Various Frequencies Using Tophet "A" Resistance Wire

Tophet "A" Resistance wire 1" Length R = 12 Ω

Frequency (mc)	Point No.	Z_R
300	1	10.0 + j 47.0
400	2	11.0 + j 65.0
500	3	1.5 + j 82.5
600	4	1.7 + j 99.5
700	5	2.1 + j 125.0
800	6	2.5 + j 151.0
900	7	3.5 + j 195.5
1000	8	3.75 + j 209.0

Table I

IMPEDANCE OR ADMITTANCE COORDINATES

R= 12 Ω

Surge Z_o = 50 Ω

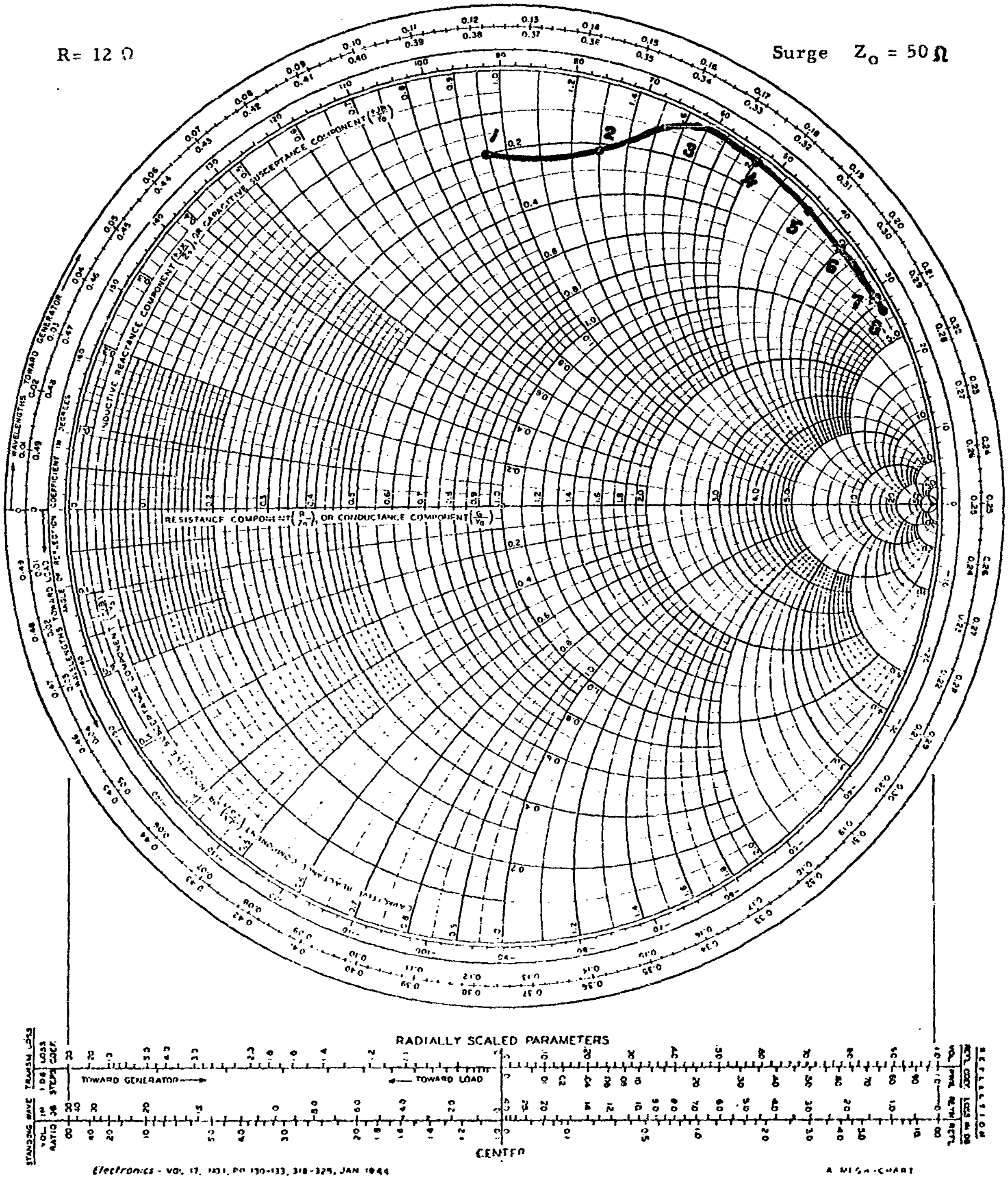


Fig. 2. Impedance Measurements at Various Frequencies Using Tophet "A" Resistance Wire

Impedance Measurements at Various Frequencies Using "Tophet" A 0.002" Resistance Wire

Length of wire = 2"   R = 26 Ω

Frequency (mc)	Point No.	Z_R (Ω)
50	1	30.50 + j 20.50
100	2	37.25 + j 56.25
150	3	25.50 + j 55.00
200	4	29.00 + j 82.50
250	5	27.50 + j 105.00
300	6	22.50 + j 110.00
400	7	35.00 + j 147.50
500	8	50.00 + j 213.00
600	9	150.00 + j 435.00
700	10	300.00 + j 605.00
800	11	50.00 - j 285.00
900	12	50.00 - j 312.00
1000	13	715.00 - j 920.00

Table II

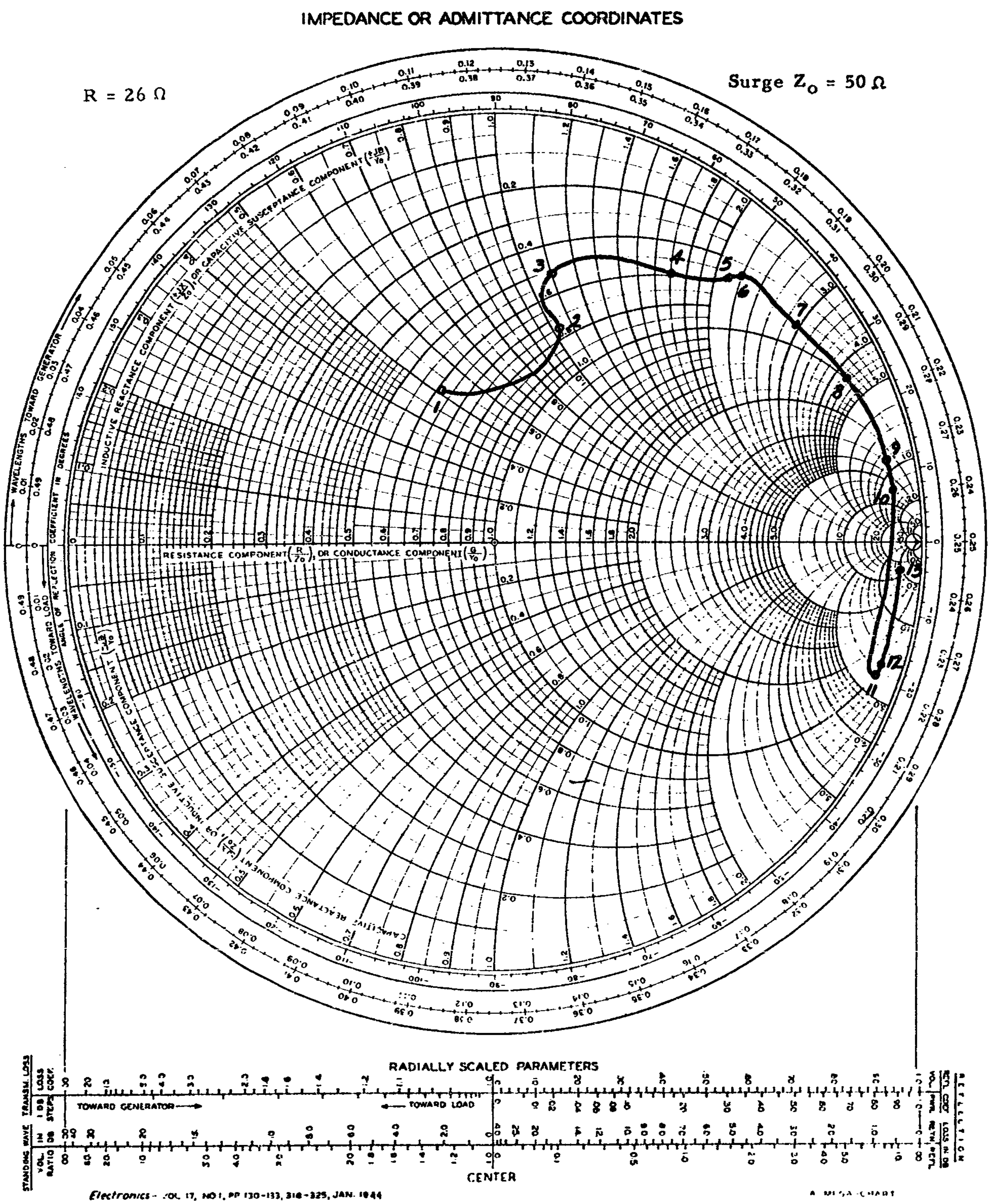


Fig. 3 - Impedance Measurements at Various Frequencies Using Tophet "A" 0.002" Resistance Wire

Impedance Measurements at Various Frequencies Using Erie Resistor Corporation Cylindrical Capacitance Titanate Unit

(Sample #2 Cluster of three (3) units from lot received on 10 January 1961)

$C = 0.52\ \mu f$ Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No.	Z_R (Ω)
300	1	$0.59 + j\ 18.1$
400	2	$0.95 + j\ 25.8$
500	3	$1.25 + j\ 29.0$
600	4	$0.50 + j\ 37.5$
700	5	$1.50 + j\ 47.0$
800	6	$2.00 + j\ 58.0$
900	7	$2.50 + j\ 67.0$
1000	8	$3.75 + j\ 85.5$

Table III

C = 0.52 μf

Surge $Z_o = 50\ \Omega$

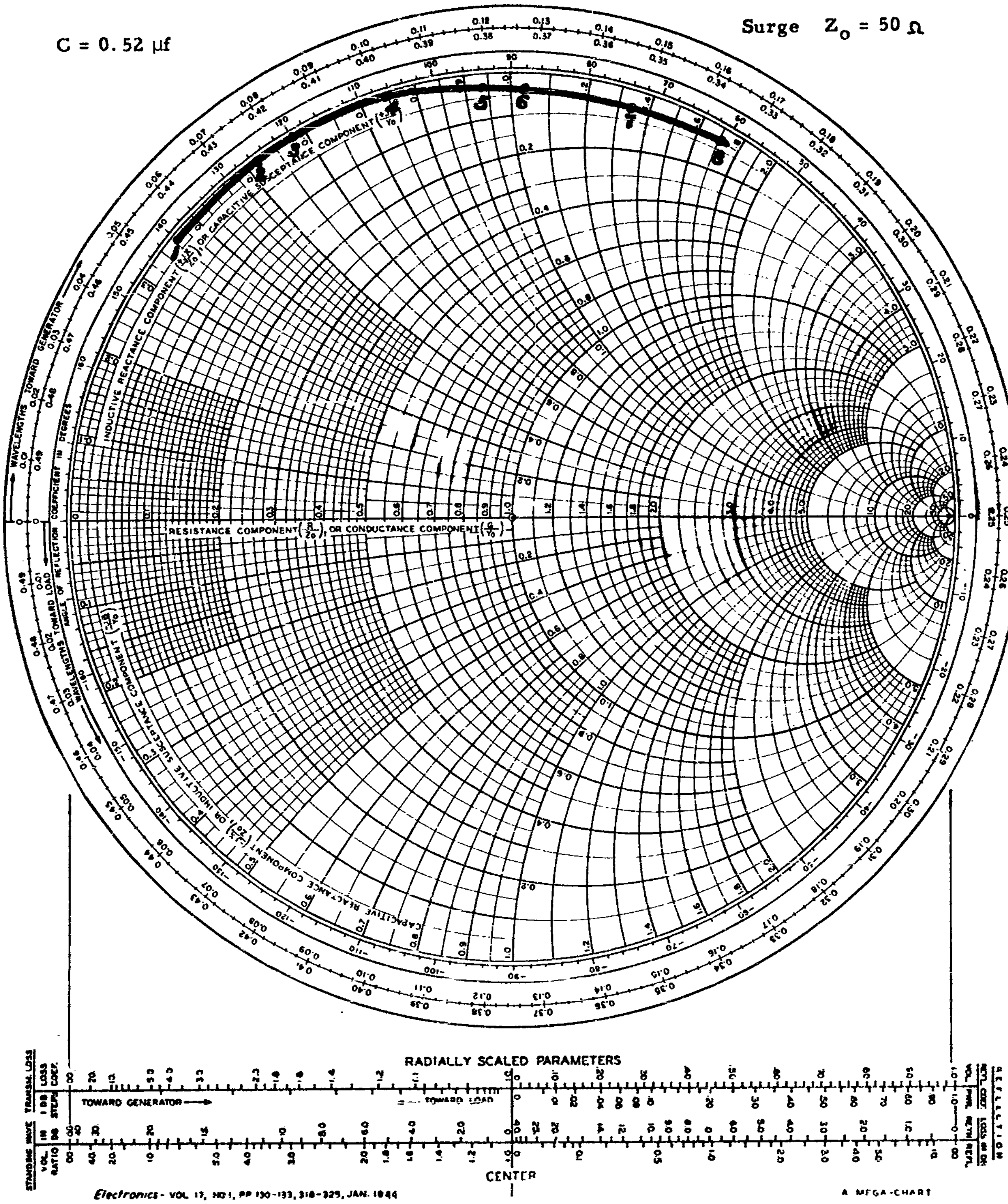


Fig. 4 - Impedance Measurements at Various Frequencies Using Erie Resistor Corporation Cylindrical Capacitance Titanate Unit
(Sample #2 Cluster of three (3) Units from lot received on 10 January 1961)

Impedance Measurements at Various Frequencies of a Paralleled Combination of a Bridge Wire Element and an Erie Resistor Corporation Cylindrical Capacitance Unit

(Cluster of three (3) units from lot received on 10 January 1961)

$C = 0.53\ \mu f$ $R = 29\ \Omega$ Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No.	Z_R (Ω)
300	1	1.55 + j 29.50
400	2	1.40 + j 29.85
500	3	0.25 + j 35.00
600	4.	0.20 + j 53.50
700	5	0.20 + j 72.50
800	6	0.30 + j 87.00
900	7	0.67 + j 97.50
1000	8	12.75 + j 122.25

Table IV

IMPEDANCE OR ADMITTANCE COORDINATES

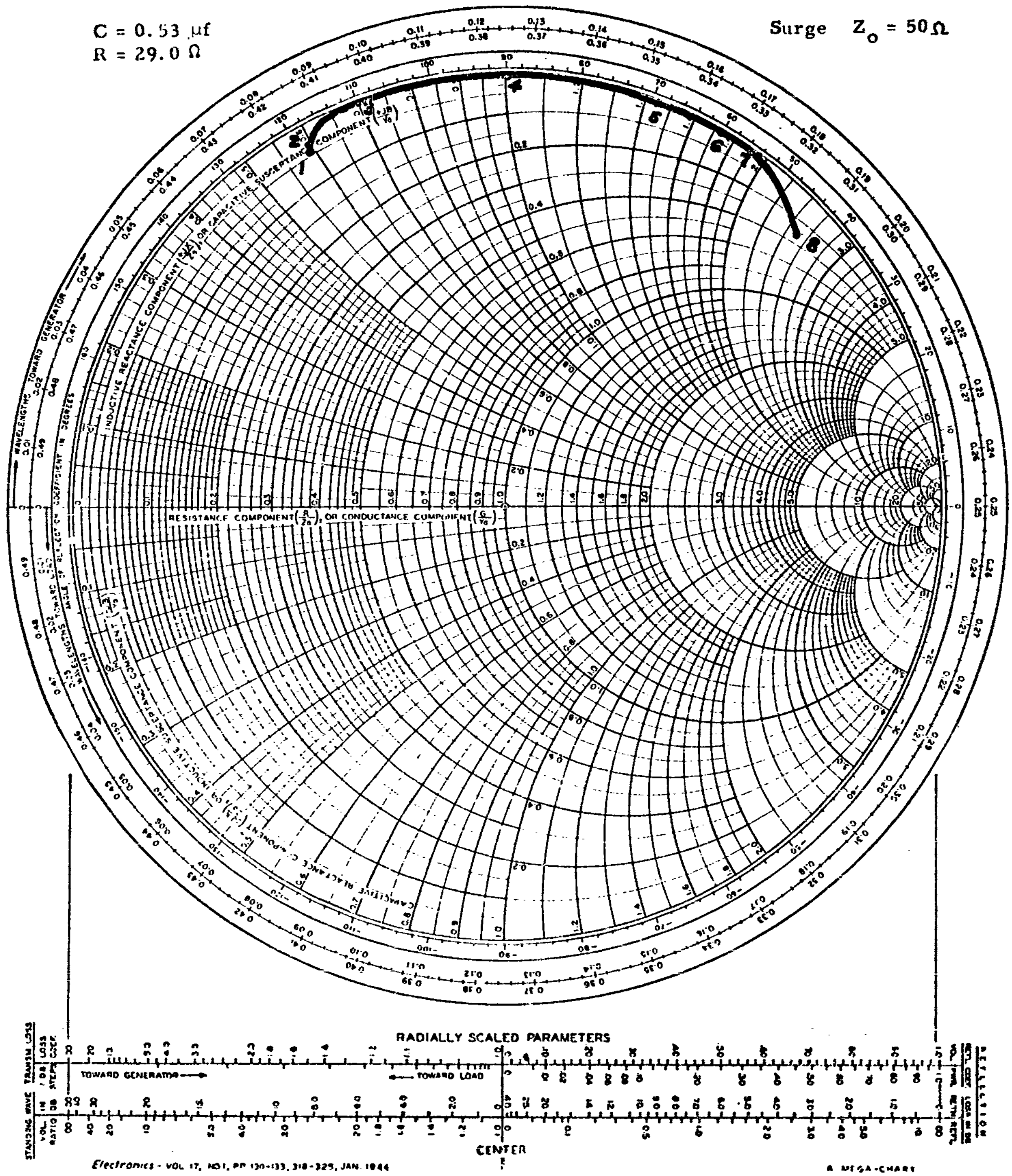


Fig. 5 - Impedance characteristic of the paralleled combination of an Erie Resistor Corporation capacitance unit and a bridge wire at frequencies from 3000 mega-cps to 1000 mega-cps

III. REACTANCE UNITS

A. DESCRIPTION

Reactance units investigated for possible application to electroexplosive match protection were basically ceramic capacitors employing two different classes of dielectric. Dictating this choice are economy and the very high ratios of capacity to volume that such units offer. One of the two classes of dielectric, a class understood to be in a developmental stage yet, and lacking an established chemical or physical designation, was characterized by an extremely high dielectric constant, of the order of 100,000 according to bridge measurements; by polarization; by high power factors, these ranging from 10.0% to 30.0%; and by a capability to sustain only low voltages, generally less than 5.0 volts. Properties of a representative lot of capacitance elements having this class of dielectric are presented in Table V. The second and more extensively studied class of dielectric is identified with the barium titanates. Capacitors made with this latter dielectric exhibited dielectric constants of 2000 to 12,000; they had low power factors, less than 0.25%; the polarization thereof appeared inconsequential; aging, that is, capacitance change with time subsequent to manufacture, was small; and all capacitors were capable of withstanding continually a d-c potential of 60.0 volts or more. As before, static or low-frequency properties of a representative lot of capacitance units embodying this class of dielectric are listed in Tables VI and VII.

No physical restrictions were made applicable to capacitor samples submitted for initial examination with the result that they came in various forms, as may be seen in Photograph 1. There shown are a parallel plate type, disc types, tubular types, and cylindrical and partitioned cylindrical types. Similarly, no limits were imposed upon capacity values of samples with the result that they spanned a wide range. Taking into account units made with the two classes of dielectric described, the lower and upper bounds of the capacity range were 0.08 mfd to 0.70 mfd. Suppliers of the capacitance unit samples on which data are presented herein were American Lava Corporation of Chattanooga, Tennessee and Erie Ceramics Research of State College, Pennsylvania.

Capacitance units supplied in the final phases of this program by these two vendors were quite similar formally, but structurally they were notably different. Formally, the units were small cylinders. Structurally, the one concern's product (American Lava Corporation) had a fairly thick-walled dielectric, approximately 0.010 inch, a consequence of the extrusion process underlying its manufacture. Units turned out by Erie Ceramics Research, on the other hand, had a very thin-walled dielectric, one resulting from the thin film techniques to which this concern resorts.

Measurements of ac and dc Characteristics of Eight (8) Cylindrical Titanate Capacitance Units*

(Samples from lot submitted by American Lava Corporation on 22 January 1961)

Sample No.	Equivalent Series Capacitance, C_e (µf)	Dissipation Factor, D	Equivalent Series Resistance, R_e $R_e = D/\omega Ce$ (Ω)	DC Leakage Resistance, R_{dc} (Ω)	Dielectric Constant, K
1	0.306	0.280	145	>11 meg Fwd & Bkwd	
2	0.310	0.320	164	>11 meg Fwd & Bkwd	
3	0.319	0.215	107	5 meg Fwd and >11 meg Bkwd	
4	0.250	0.165	105	>10 meg Fwd & Bkwd	
5	0.282	0.280	158	3.5 meg Fwd & Bkwd	Over 100,000
6	0.416	0.312	119	10.0 meg Fwd & 10.6 meg Bkwd	
7	0.376	0.160	68	2.2 meg Fwd & >11 meg Bkwd	
8	0.335	0.220	104	>11 meg Fwd & Bkwd	

* Measurements made with GR 1650A Impedance Bridge; Test Frequency - 1000 cps

Table V

Measurement of ac and dc Characteristics of Eight (8) Cylindrical Titanate Capacitance Units *

(Samples from lot submitted by American Lava Corporation on 6 March 1961) Cluster of three (3) Units

Sample No.	Equivalent Series Capacitance, C_e (μf)	Dissipation Factor, D	Equivalent Series Resistance, R_e $R_e = D/\omega C_e$ (Ω)	DC Leakage Resistance, R_{dc} (Ω)	Dielectric Constant, K
1	0.252	0.0210	13.25	Fwd & Bkwd R_{dc} $>10^9$	Estimated to be from 5000 - 8000
2	0.253	0.0220	13.81	Fwd & Bkwd R_{dc} $>10^9$	
3	0.250	0.0270	17.20	Fwd & Bkwd R_{dc} $>10^9$	
4	0.242	0.0195	12.83	Fwd & Bkwd R_{dc} $>10^9$	
5	0.233	0.0195	13.31	Fwd & Bkwd R_{dc} $>10^9$	
6	0.270	0.0200	11.80	Fwd & Bkwd R_{dc} $>10^9$	
7	0.240	0.0230	15.24	Fwd & Bkwd R_{dc} $>10^9$	
8	0.235	0.0210	14.20	Fwd & Bkwd R_{dc} $>10^9$	

* Measurements made with ESI Model 250-DA Impedance Bridge, Test Equipment - 1000 cps

Table VI

Table VII

Measurement of A-C Characteristics of Eight (8) Cylindrical Titanate Capacitance Assembly (Cluster of three (3) Units)

Sample Units from American Lava Corporation

Sample No.	Equivalent Series Capacitance, Ce (μf)	Dissipation Factor D	Equivalent Series Resistance, R_e $R_e = \frac{D}{WC_e}$ (Ω)
1	0.270	0.0120	6.81
2	0.264	0.0115	6.96
3	0.242	0.0115	7.57
4	0.252	0.0115	7.26
5	0.271	0.0115	6.73
6	0.274	0.0115	6.70
7	0.265	0.0115	6.91
8	0.271	0.0115	6.73

* Measurements made with GR-1650A Impedance Bridge; Test Frequency - 1000 cps

Photograph 1. Typical capacitance units from lots submitted by American Lava and Erie Resistor Corporations.

B. APPLICATION CONSIDERATIONS

In the application of reactance units to squib protection consideration must be given not only to those unit characteristics which are favorable to protection but also to those which are, of themselves or when in interplay relationship with still others of conjoined elements, unfavorable. Several of these latter situations merit attention.

Capacitor imperfections, as one example, give rise to two factors which must be considered in the application of any capacitor to squib protection service. These factors are, respectively, the equivalent series resistance and reactance that any given unit presents to a signal source. Determination of both impedance components may be made quite readily at low frequencies where it is common practice to represent a capacitor by an equivalent circuit comprised of a pure resistance branch in parallel with one made up of a series-connected combination of a perfect condenser and a small resistance. If in such circuit the capacity of the unit is denoted by C, the resistance in series with it by r, and the paralleled resistance by R, then the equivalent resistance and reactance at any circular frequency, ω, according to the development in Appendix A1 are

$$R_e = \frac{R\left[1 + \omega^2 C^2 r (R + r)\right]}{1 + \omega^2 C^2 (R + r)^2} \tag{3.1}$$

and

$$X_e = \frac{\omega C R^2}{1 + \omega^2 C^2 (R + r)^2} \tag{3.2}$$

Both parameters, obviously, must have low values compared to the bridge wire resistance at all frequencies in the squib protection band. Graphical representations of these two parameters as found in the case of a special capacitor, one, incidentally, unsuitable for application to squibs, are given in Fig 6. Similar representations, produced on a curve sheet with a more contracted abscissa scale, may be found in Fig 7.

A corollary relationship developed in Appendix A1 is that for equivalent capacitance. This is given as

$$C_e = \frac{1 + \omega^2 C^2 (R + r)^2}{\omega^2 C R^2} \tag{3.3}$$

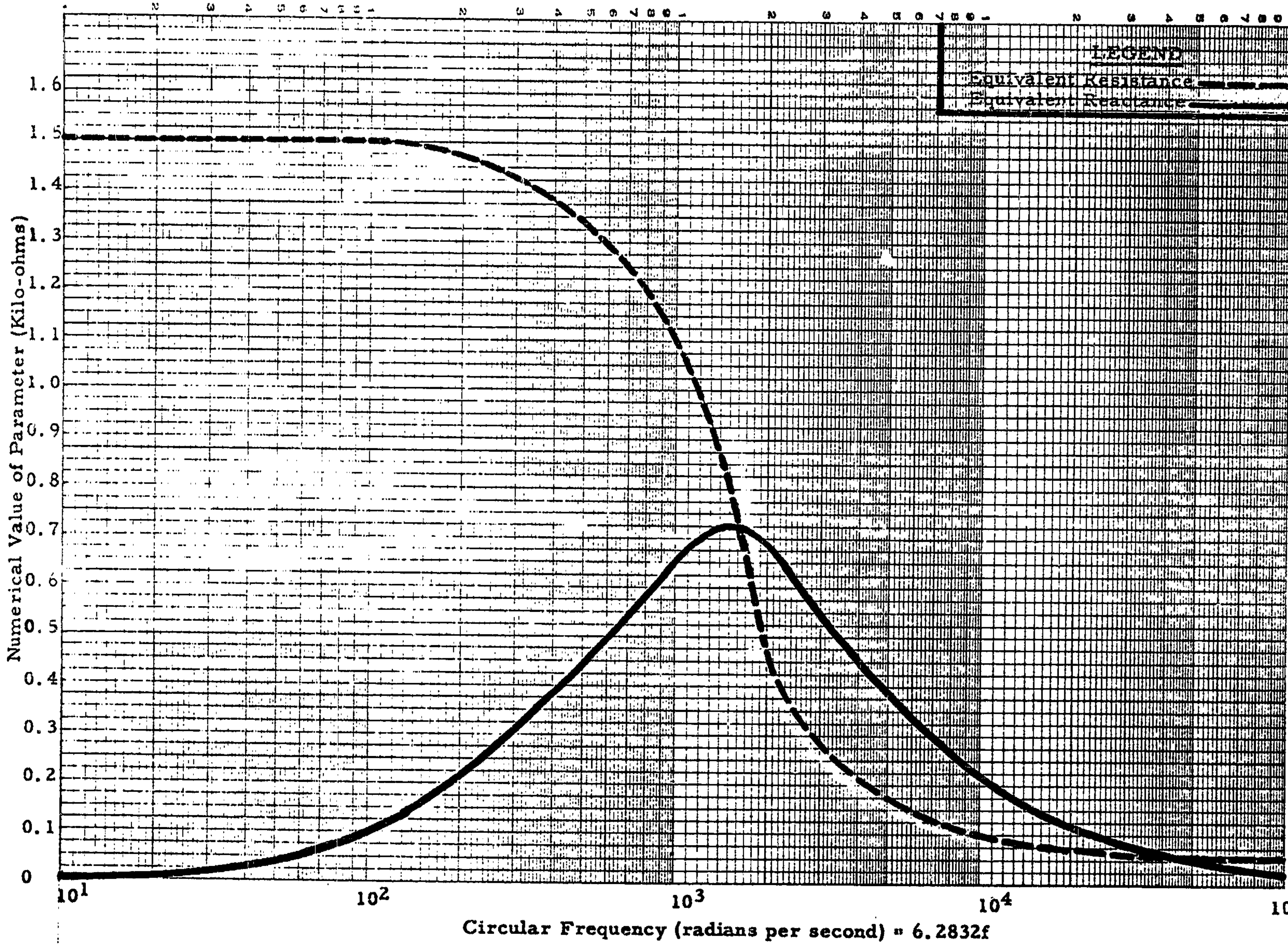
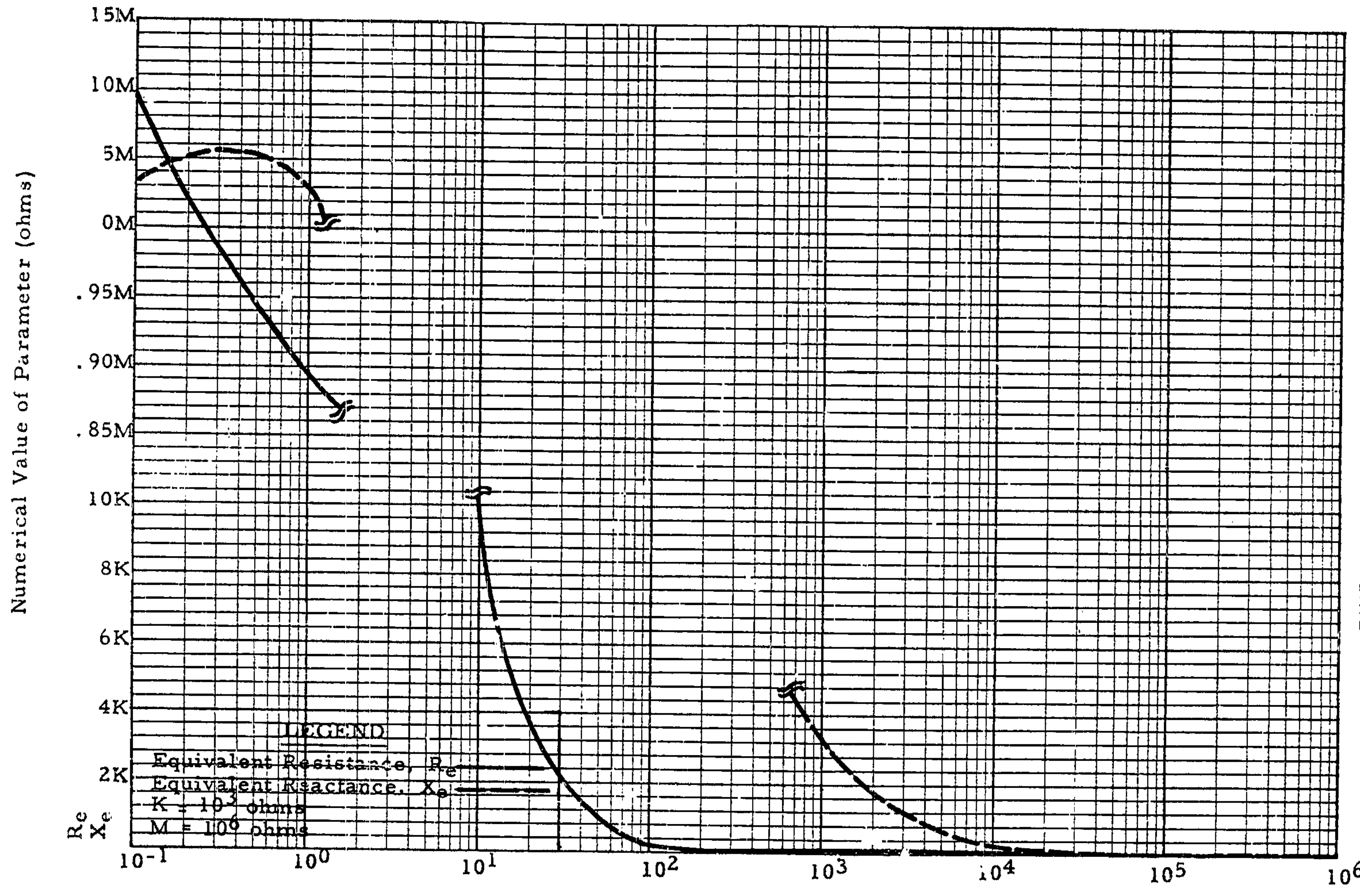


Fig. 6 - Theoretical Resistance & Reactance of a Representative Sample of a Titanate Capacitance Unit



Theoretical Resistance & Reactance Characteristics Exhibited by Cylindrical Titanate Capacitance Units
(Sample from lot submitted by American Lava Corporation on 22 January 1961)
Fig. 7

Fig. 8 , in turn, shows how C_ε varies as a function of frequency.

Of possible interest about the expression for equivalent reactance are two results that were obtained in the analysis constituting Appendix A2. First is the frequency at which the reactance is a maximum, namely

$$\omega_M = \frac{1}{C\,(R + r)} \tag{3.4}$$

and the second is the value of that reactance, viz.

$$(X_e)_M = \frac{R^2}{2\,(R + r)} \tag{3.5}$$

Another factor requiring consideration in the application of capacitors is prevention of the establishment of a resonant circuit system within the match wiring. Such a system may be formed easily in the mesh comprised of the capacitor and bridge wire branches. These two may appear at moderate radio-frequencies to be a capacitance-resistance path in parallel with an inductance-resistance path. If, now, in the former the capacitance be denoted by C and the resistance in series with it by R_C, and, if in the latter the inductance be designated by L and the series resistance by R_L then, as shown in Appendix A3, the condition requiring fulfillment to assure non-occurrence of a resonant state (10) is that

$$\left[\frac{L - CR_L^2}{L - CR_C^2}\right] \leqslant 0 \tag{3.6}$$

Giving rise to a third application consideration are the physical forms of the reactance units used to provide squib protection. Most capacitance elements have tubular shapes, embodying paralleled electrodes of high conductivity material. These last, in essence, cause the elements to appear as open transmission line stubs. Accordingly, the reactance they display is essentially that given by the expression

$$X = -j\, Z_o \cot \beta s \tag{3.7}$$

where Z_o signifies the characteristic impedance of the capacitor line, β = phase constant, and s is the length of the electrodes.

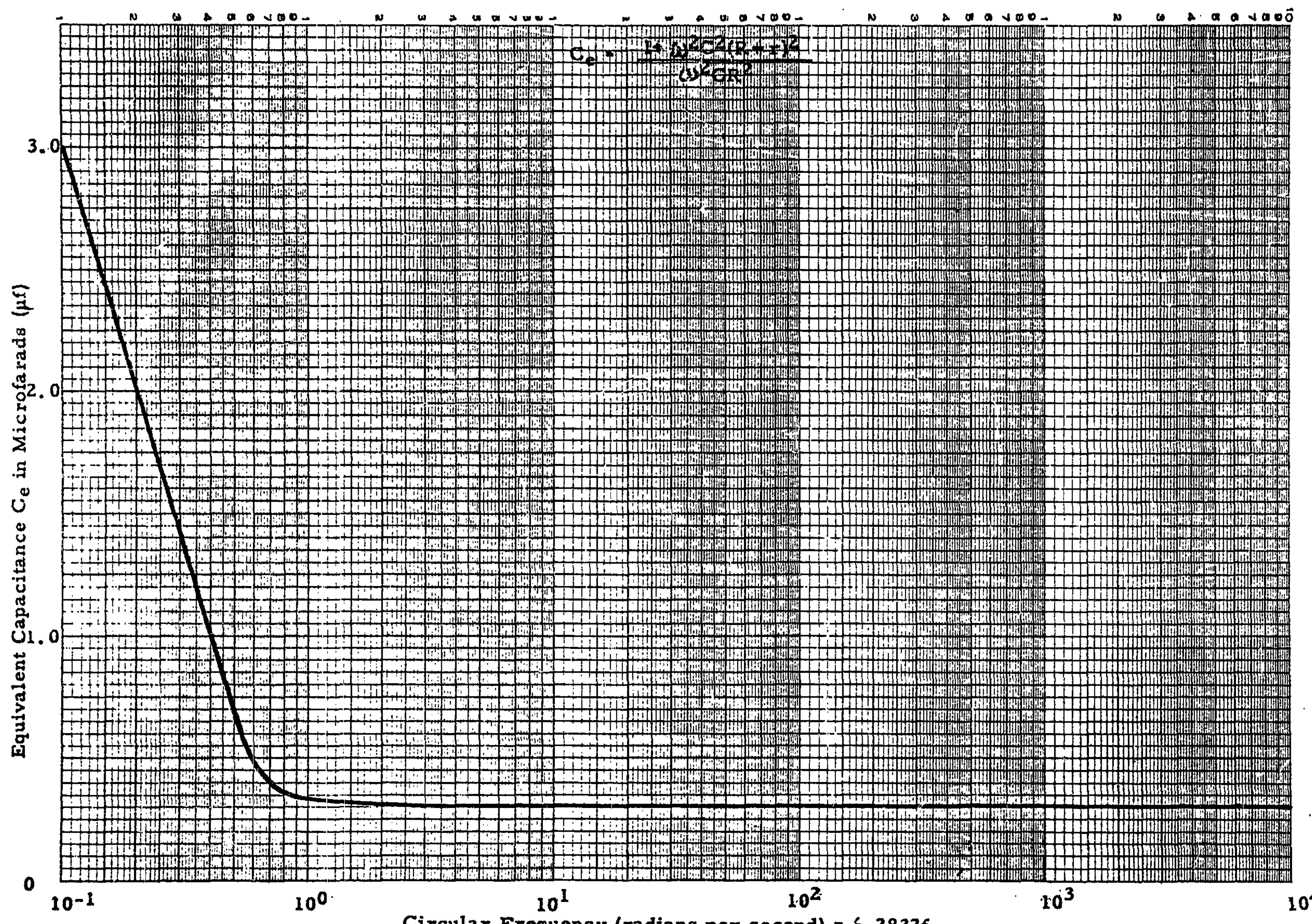


Fig. 8 - Equivalent Series Capacitance as a function of Circular Frequency of Cylincrical Titanate Capacitance Units Sample # 1 (American Lava Corporation)

IV. INVESTIGATIVE OPERATIONS

A. APPARATUS

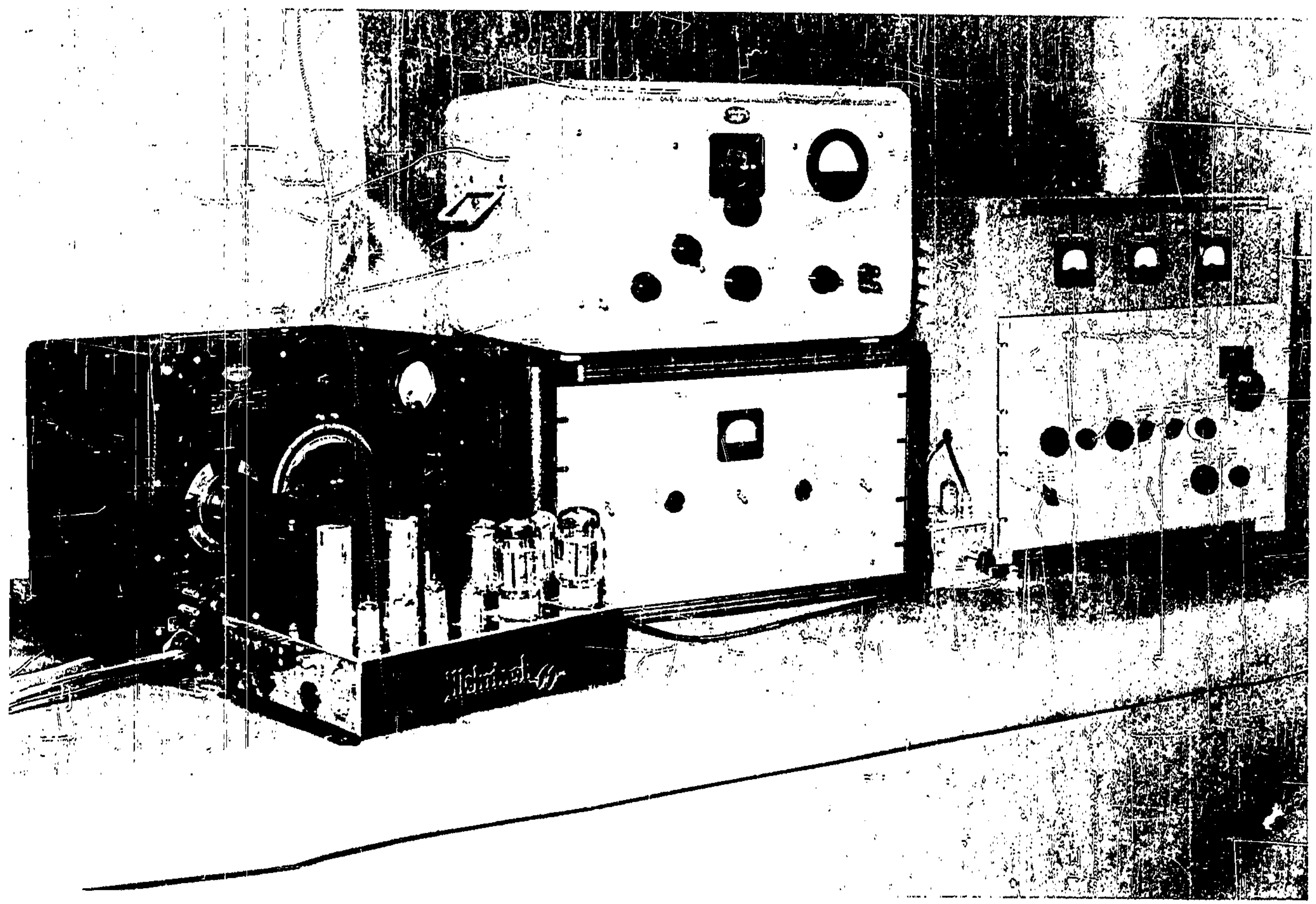
In order to attain the required objective, the contractor was obligated to procure and fabricate R. F. power generating equipment to provide a minimum output of 50 watts C. W. power over the frequency band of 400 cycles to 11 KMC per second. The equipment referred to above is shown in the accompanying photographs, numbered 2 to 6 inclusive.

Shown in Photograph 2 is the equipment utilized to cover the frequency range from 400 cycles to 50 MC per second. The power sources consist of a McIntosh MC-60 audio power amplifier, covering the frequency range from 400 cycles to 100 KC per second, while the frequency range from 100 KC to 50 MC per second is covered by the band-switching power amplifier fabricated by the contractor. Included in Figures 9 through 12 are the basic schematics of the band-switching power amplifier.

Photograph 3 shows the equipment covering the frequency range from 50 MC to 1000 MC per second. The equipment consists of Sierra Models 215A-150, 215A-470 and 215A-1000, power oscillators.

The equipment required to cover the frequency range between 1 and 11 KMC per second is shown in Photograph 4. This equipment consists of a Micro-Tel MPS-110 power supply and modulator, MIB magnetron mount, and one each L, C and X-band magnetron, each providing a minimum of 50 watts C. W. power output and covering the frequency ranges respectively of 960-1500, 4900-6100 and 8650-10,500 MC per second.

In addition to the required power sources, shown in Photographs 2 through 6 is the major part of the auxiliary equipment required to obtain the data presented in this report. This equipment includes a PRD type 650-B power bridge, type 277B standing wave amplifier, type 504 heterodyne frequency meter, type 250A slotted line, General Radio type 874-LBA slotted line, type 1062-A admittance meter, and various line terminations.



Photograph 2. View of signal sources covering VLF through VHF frequency spectrum.

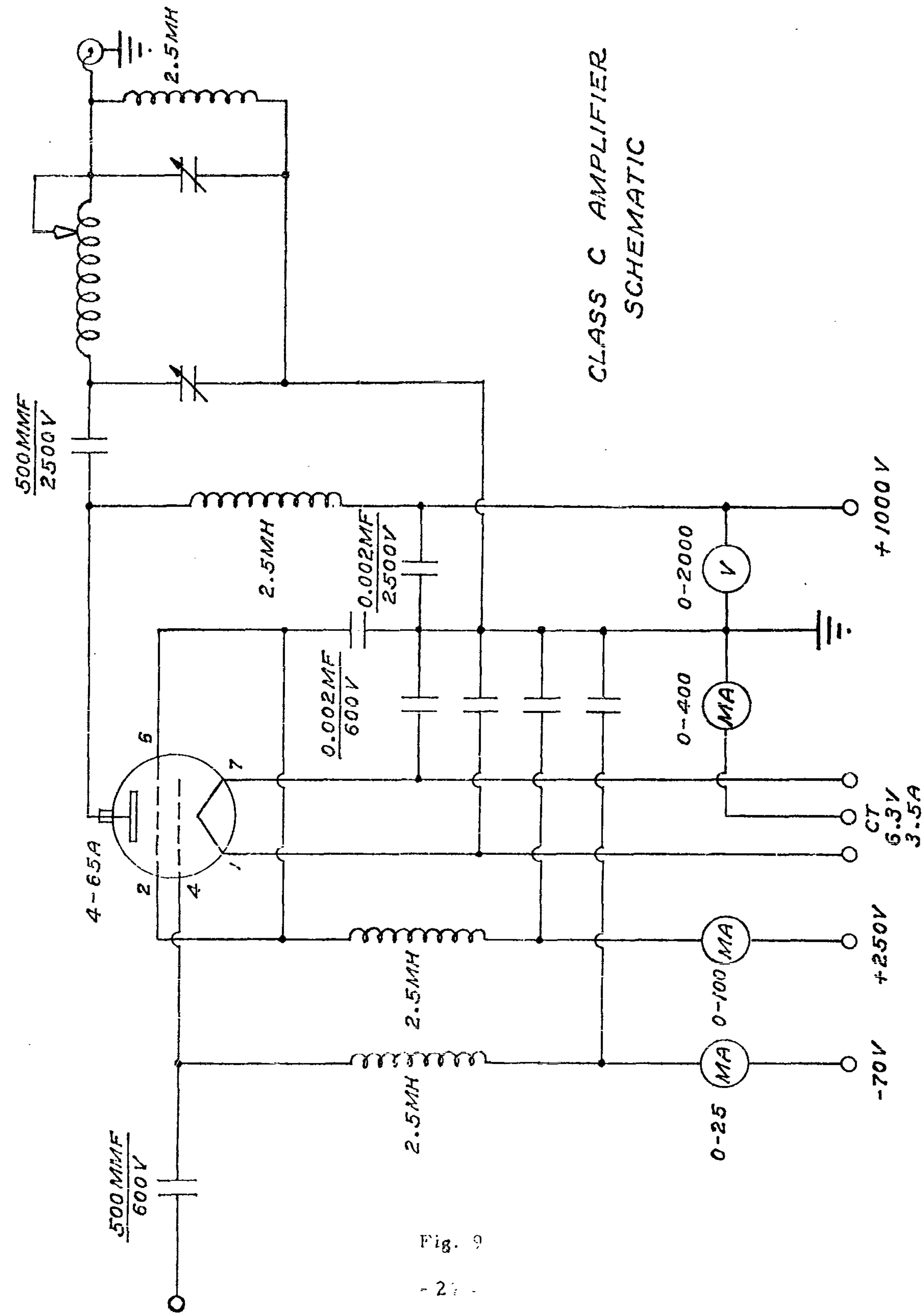
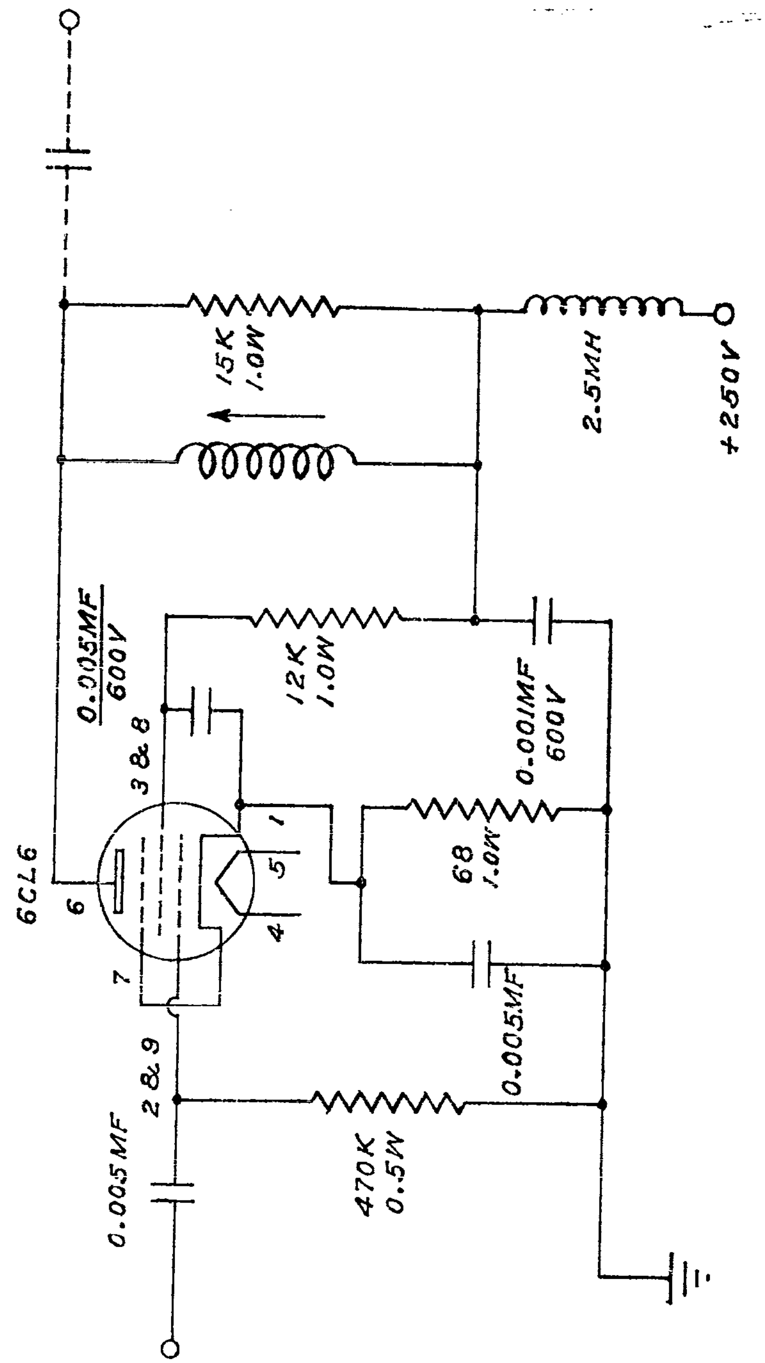

CLASS C AMPLIFIER
SCHEMATIC
2.5MH
500MMF
2500V
2.5MH
0.002MF
2500V
0.002MF
600V
4-65A
2.5MH
2.5MH
500MMF
600V
0-2000
V
0-400
MA
0-100
MA
0-25
MA
+1000V
CT
6.3V
3.5A
+250V
-70V

Fig. 9



CLASS A AMPLIFIER SCHEMATIC

Fig. 10

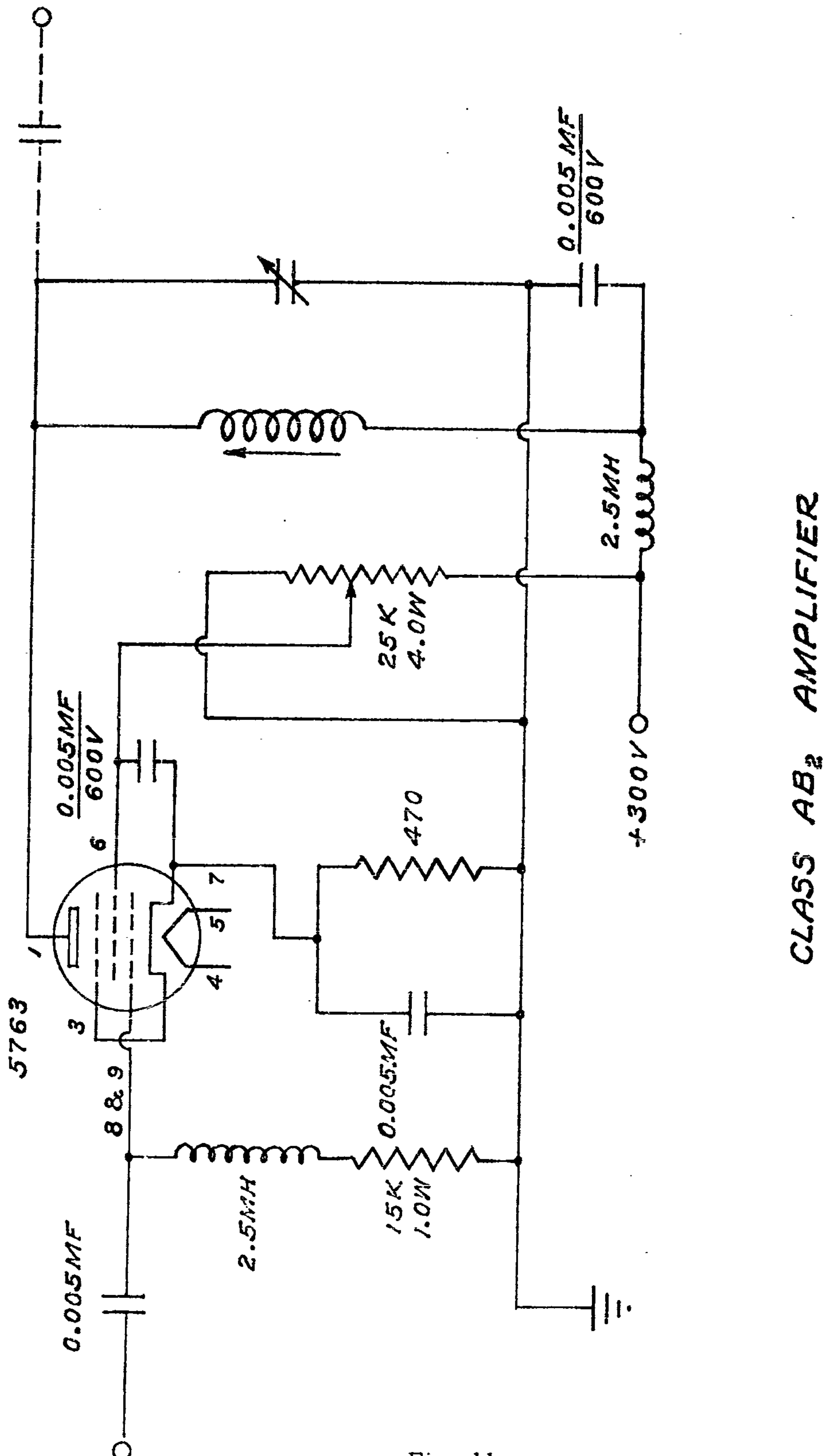

CLASS AB2 AMPLIFIER
0.005 MF
600 V
2.5MH
25 K
4.0W
+300V
470
0.005MF
600V
5763
1
3
6
7
5
4
8 & 9
0.005MF
2.5MH
15K
1.0W
0.005MF

Fig. 11

POWER AND BIAS SUPPLY SCHEMATICS

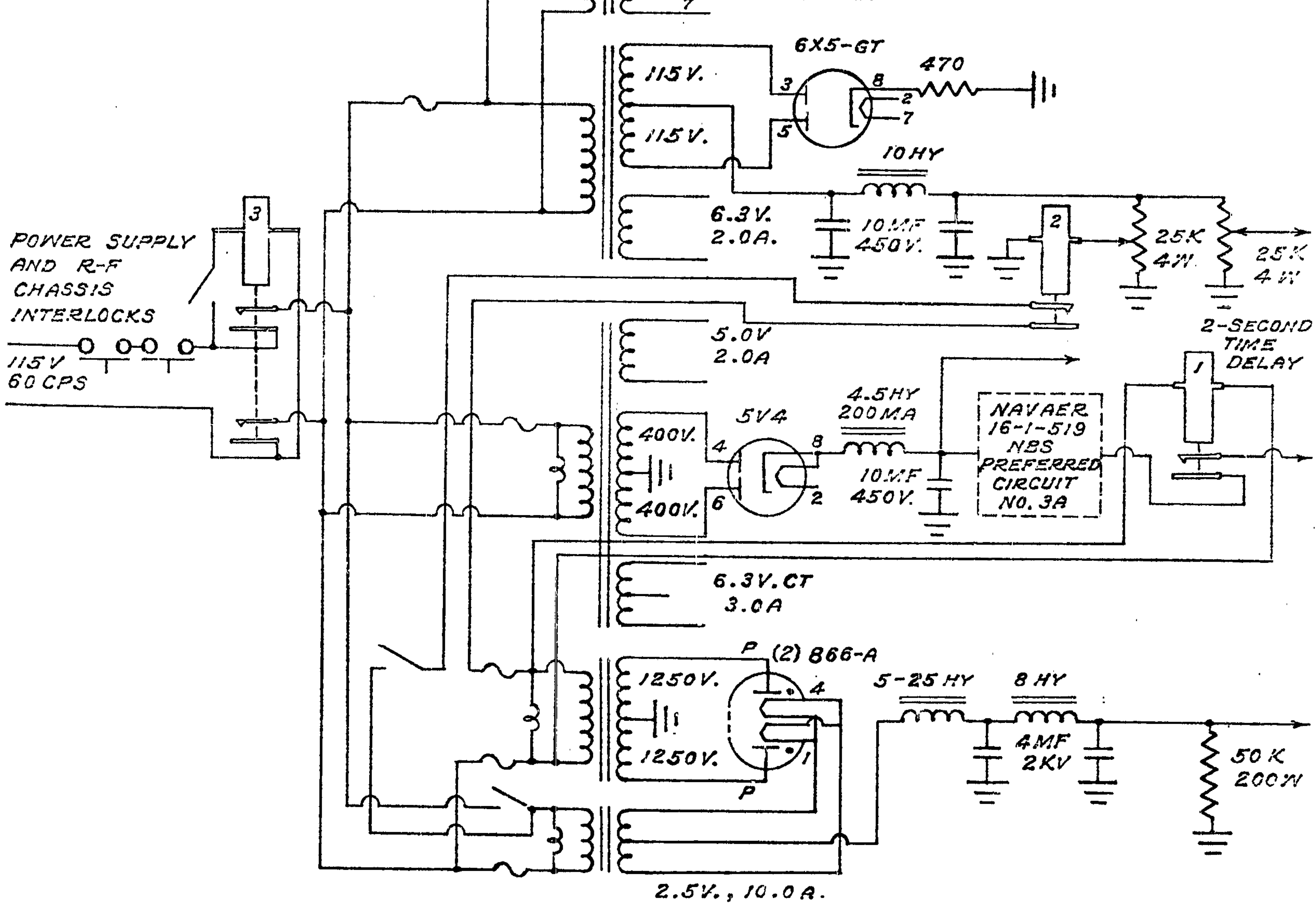
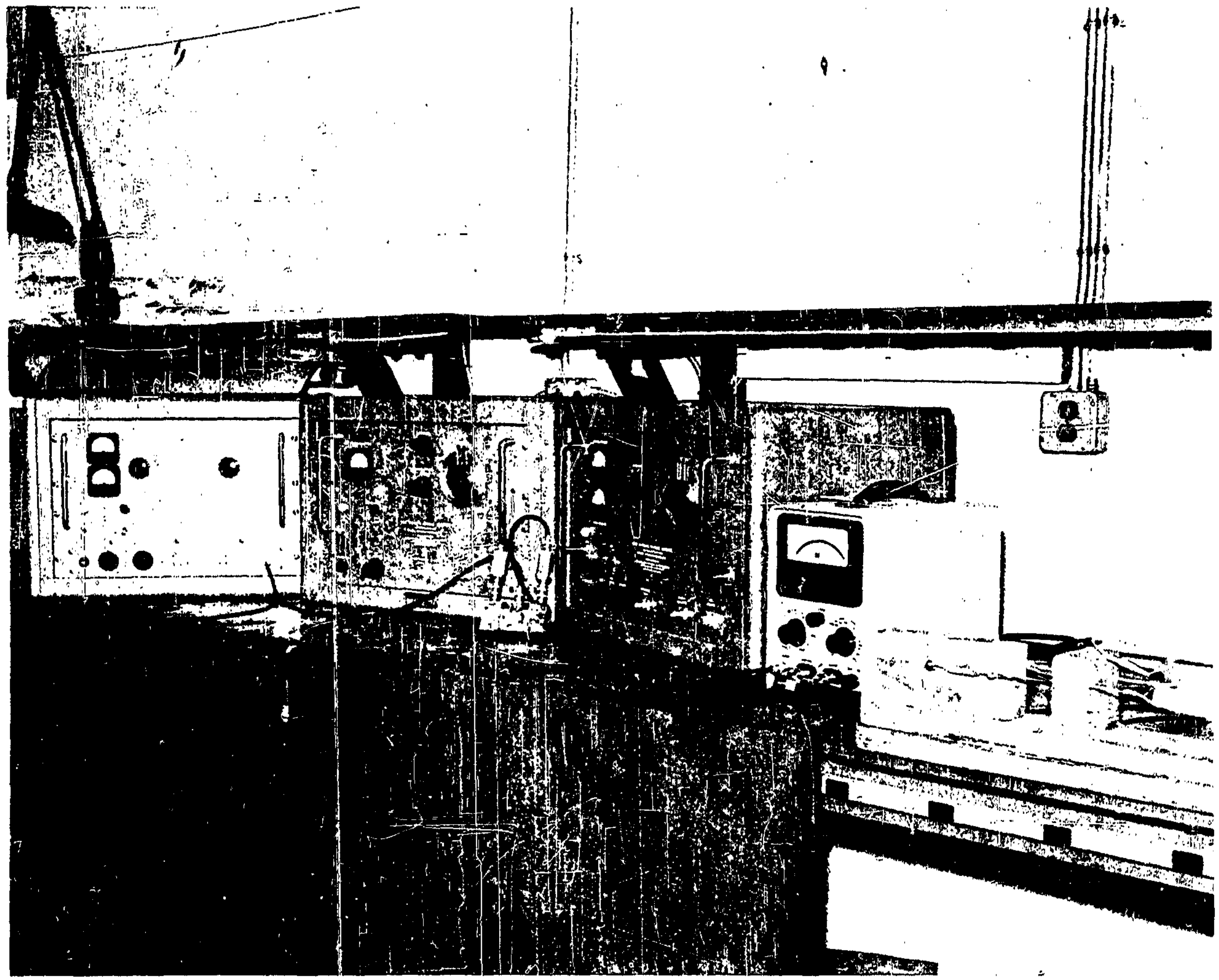
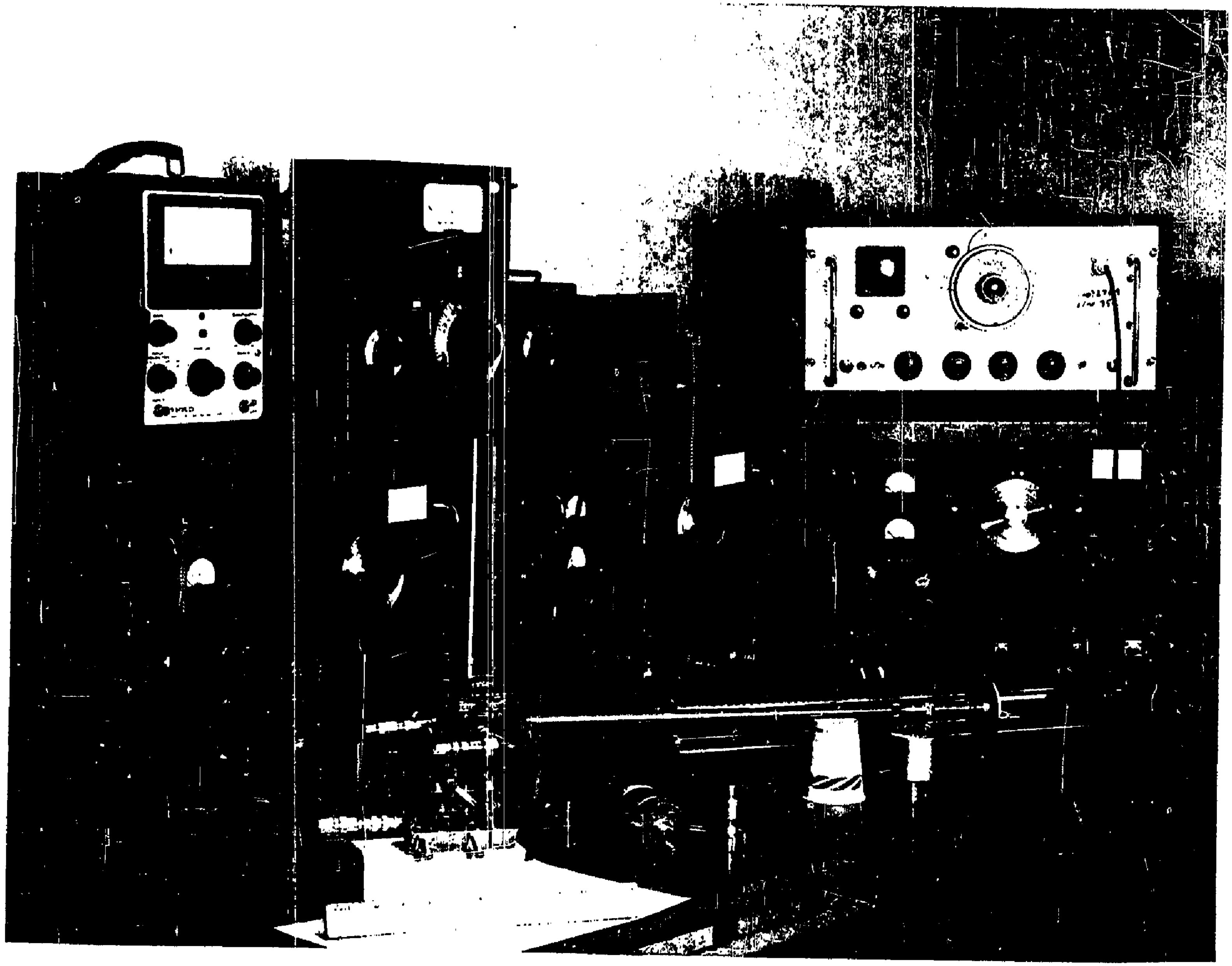


Fig. 12



Photograph 3. View of the VHF and UHF signal sources, Voltage Standing Wave Ratio meter and squib simulation set-up.

Photograph 4. View of microwave impedance and power measurement apparatus, together with squib detonating chamber



Photograph 5. View of VHF and UHF signal sources, impedance measurement apparatus, and squib simulation set-up.

Photograph 6. View of microwave power measurement apparatus and squib detonating chamber.

B. TESTS OF REACTANCE UNITS ALONE

This section describes tests made on capacitance units alone, before inclusion into the simulated test fixture utilized to obtain test data on the complete squib assembly.

The capacitance units evaluated during the course of this program were subjected to two basic types of tests, both types conducted under static conditions. In the first type of test, the unit was placed in a capacitance bridge, General Radio Capacitance Bridge Model 1650-A, and the capacitance, shunt d-c resistance and the dissipation factor measured. Data on typical samples was recorded in Tables V through VII, and is included in Section III, entitled Reactance Units.

Secondly, the sample was evaluated throughout the frequency range from 50 MC to 1000 MC per second, utilizing a General Radio Admittance Meter, model 1602-B, in conjunction with the necessary signal sources to cover the required frequency range. A typical laboratory measurement set-up is shown in photograph 5. Smith chart plots were made of the data thus obtained, indicating the performance of the sample on an impedance versus frequency basis.

Data from this test is shown in figures 13 through 15. As indicated in figures 13 and 14, the capacitance units evaluated exhibit a smooth impedance cuver over the entire frequency range, while the curve in figure 15 is not a smooth one, indicating an undesirable capacitance unit.

The primary objective in conducting the static tests was to eliminate capacitance units exhibiting any undesirable behavior from the lot that would ultimately be incorporated into the final squib design.

Impedance Measurements at Various Frequencies Using Erie Resistor Corporation Production Model Cylindrical Titanate Capacitance Assembly (Cluster of three (3) units), with Teflon Insulated Wire Externally Connected to Assembly, and Ceramic Mount Without Bridge Wire,

$C \approx 0.5\ \mu f$ Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No.	Z_L (Ω)
50	1	0 + j 82.5
70	2	0 + j 12.5
100	3	0 + j 16.5
150	4	0 + j 24.5
200	5	0 + j 32.0
250	6	0 + j 40.5
300	7	0 + j 49.5
350	8	0 + j 60.0
400	9	0 + j 71.0
450	10	0 + j 85.0
500	11	0 + j 82.5
550	12	0 + j 110.0
600	13	0 + j 125.0
650	14	0 + j 140.0
700	15	0 + j 160.0
750	16	0 + j 195.0
800	18	0 + j 260.0
850	18	0 + j 320.0
900	19	0 + j 600.0
950	20	0 + j 1500.0
1000	21	0 + j 2000.0

Table VIII

C ≈ 0.5μf

IMPEDANCE OR ADMITTANCE COORDINATES

Surge Z_o = 50Ω

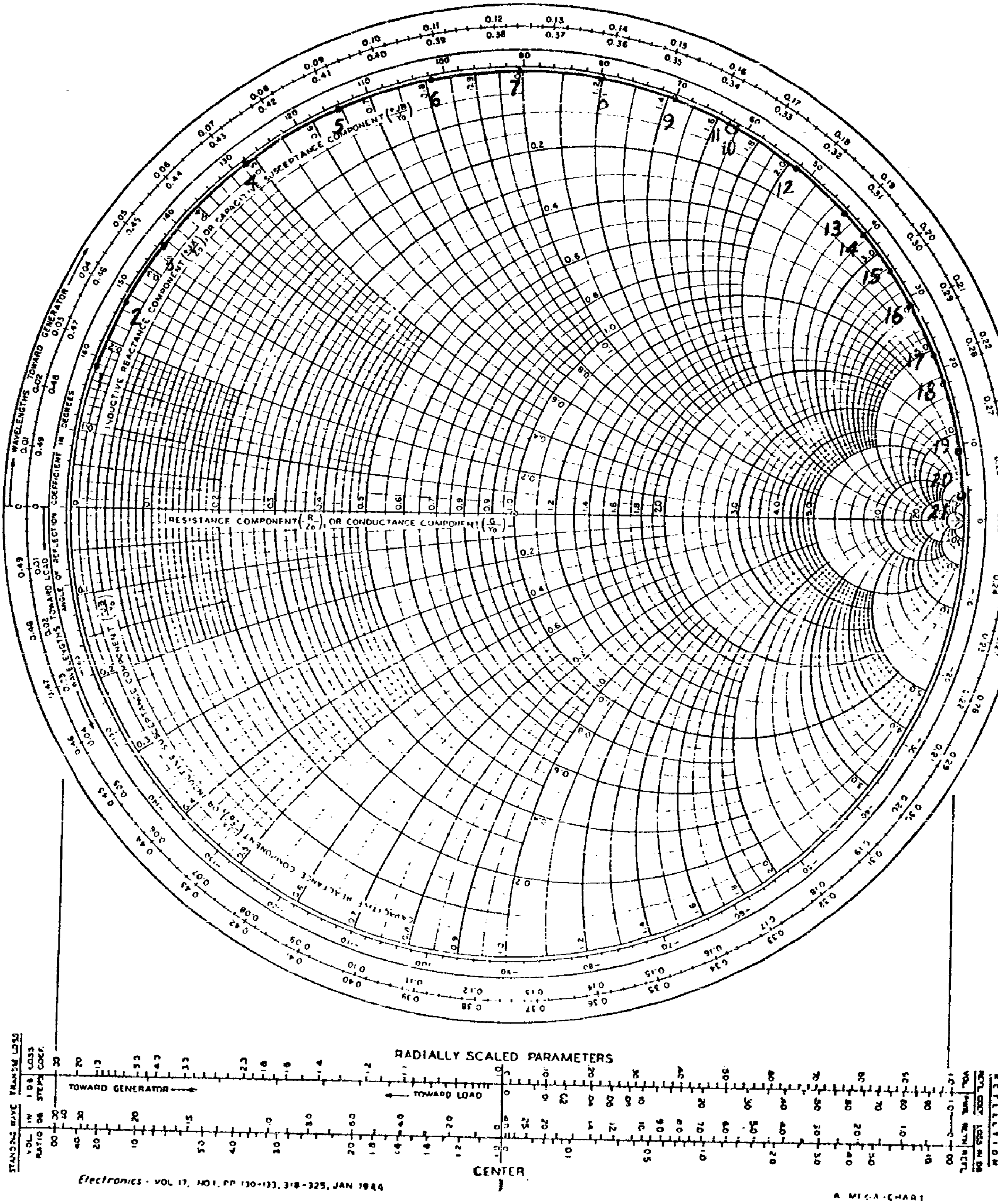


Fig. 13 - Impedance Measurements at Various Frequencies Using Erie Resistor Corporation Capacitance Assembly

Impedance Measurements at Various Frequencies Using American Lava Corporation Cylindrical Capacitance Unit (Cluster of three (3) units), Hermetic seal and Ceramic Mount without Bridge Wire

American Lava Corp. #4; C = 0.252 μf; Surge Z_o = 50 Ω

Freq (mc)	Point No.	Z_L (Ω)
50	1	0 + j 7.6
70	2	0 + j 10.5
100	3	0 + j 16.0
150	4	0 + j 20.5
200	5	0 + j 25.5
250	6	0 + j 33.0
300	7	0 + j 40.5
350	8	0 + j 49.0
400	9	0 + j 58.0
450	10	0 + j 65.5
500	11	0 + j 65.5
550	12	0 + j 80.5
600	13	0 + j 92.5
650	14	0 + j 107.5
700	15	0 + j 125.0
750	16	0 + j 145.0
800	17	0 + j 182.5
850	18	0 + j 230.0
900	19	0 + j 300.0
950	20	0 + j 800.0
1000	21	0 + j ∞

Table IX

IMPEDANCE OR ADMITTANCE COORDINATES

C = 0.252 μf

Surge Z_o = 50Ω

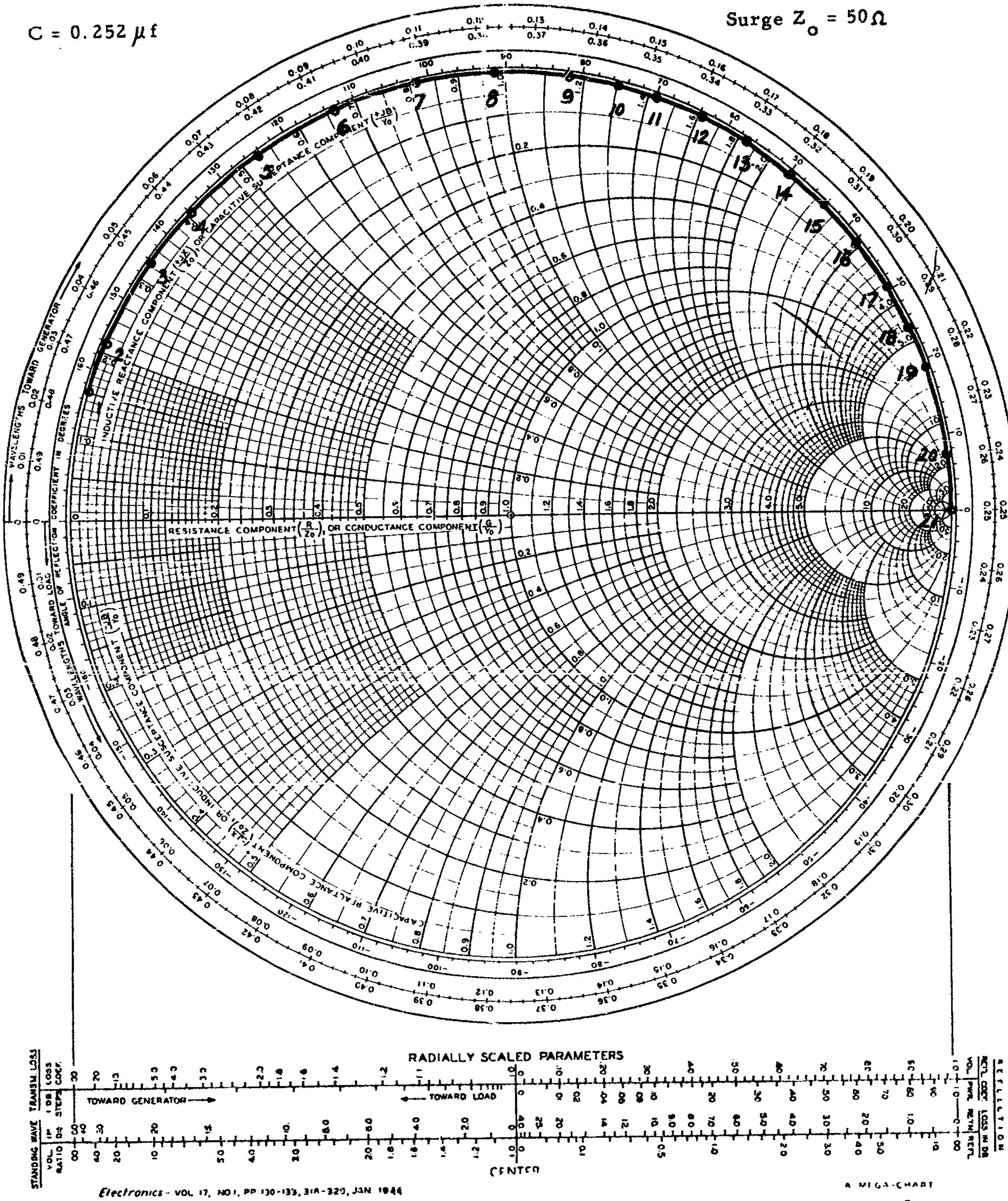


Fig. 14 - Impedance Measurements at Various Frequencies Using American Lava Corporation Capacitance Assembly

Impedance Measurements at Various Frequencies Using Erie Resistor Corporation Cylindrical Capacitance Assembly (Cluster of three (3) Units) and Ceramic Resistance Wire Mount

$C = 0.42\ \mu f$ Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No.	Z_R (Ω)
50	1	0.50 + j 6.75
60	2	0.25 + j 10.00
70	3	0.25 + j 9.4
80	4	0.50 + j 11.3
90	5	0.40 + j 12.0
100	6	0.0 + j 12.5
110	7	0.0 + j 13.6
120	8	0.0 + j 14.8
130	9	0.25 + j 16.8
140	10	1.00 + j 17.5
150	11	1.00 + j 18.3
175	12	1.00 + j 20.8
200	13	1.25 + j 23.6
225	14	1.25 + j 27.0
250	15	0.75 + j 29.0
275	16	0.75 + j 34.2
300	17	0.75 + j 38.0
350	18	0.75 + j 48.0
360	19	2.25 + j 48.8
370	20	2.50 + j 52.0
380	21	3.00 + j 51.0
390	22	3.25 + j 52.5
400	23	5.25 + j 55.0
425	24	5.50 + j 53.8
450	25	12.0 + j 60.0
475	26	20.3 + j 51.4
500	27	17.5 + j 55.0
550	28	26.8 + j 87.5
600	29	76.5 + j 115.0
650	30	61.0 - j 19.0
700	31	14.3 + j 22.5
750	32	6.3 + j 47.8
800	33	5.0 + j 65.0
900	34	5.0 + j 98.0
1000	35	10.0 + j 150.0

Table X

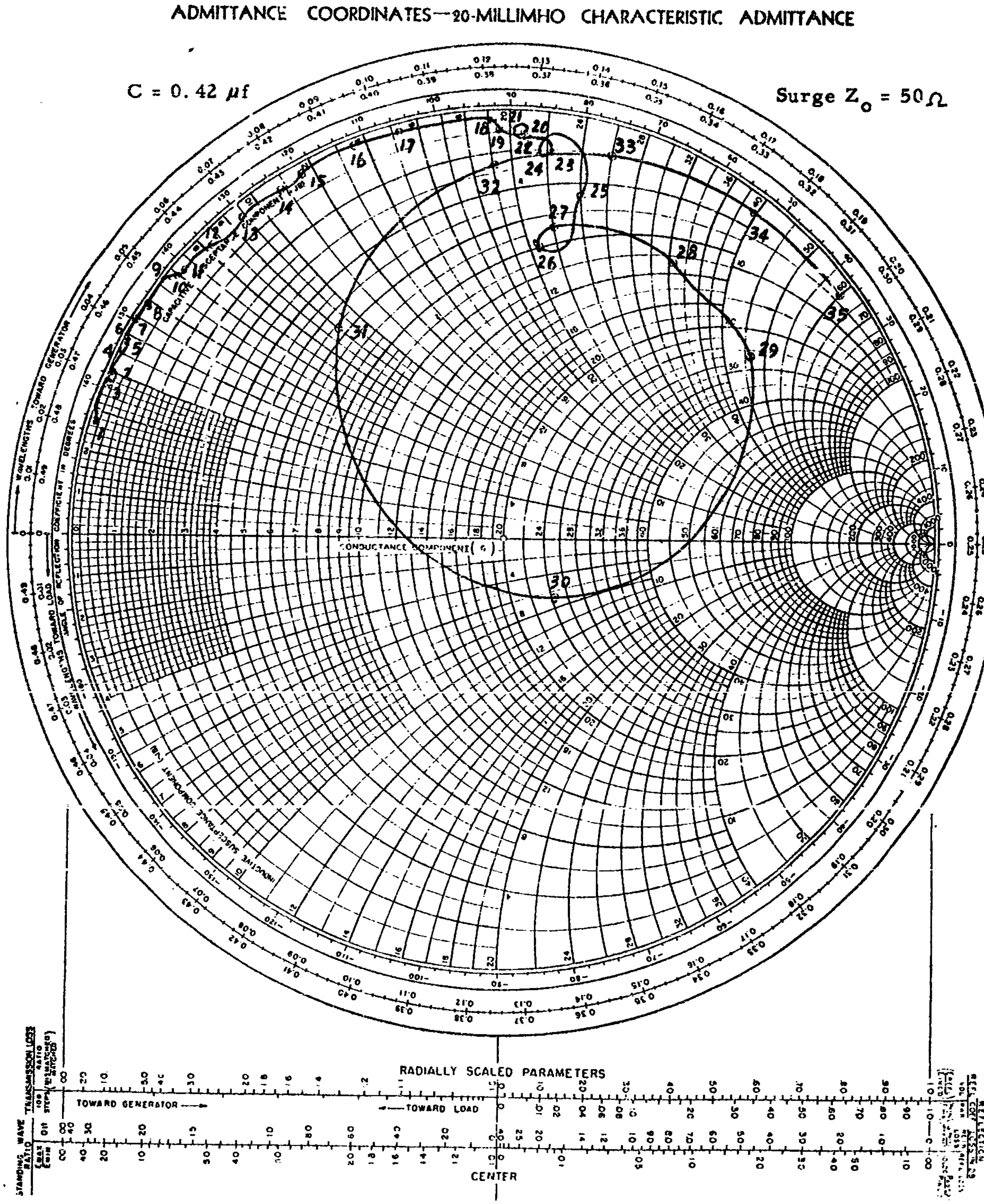


Fig. 15 - Impedance Measurements at Various Frequencies Using Erie Resistor Corporation Cylindrical Capacitance Unit (Cluster of three (3) Units) and Ceramic Resistance Wire Mount

C. Tests of Reactance Units In Simulated Set-Ups And Complete Squib Assemblies

1. Measurement Techniques:

Since the effectiveness of capacitance units to insensitize squibs to radio frequency influences is the matter of interest in this study, main attention has been given to the characteristics and performance of the units themselves. Secondary attention only has been given to the other elements comprising the complete squib assembly. Capacitance unit characteristics were determined in a number of ways, the methods used depended largely on the particular operating frequency range. For example, at low frequencies these characteristics were found by conventional bridge methods, a General Radio Company Type 1650A impedance bridge being used; at the higher audio frequencies and supersonic frequencies data was obtained with ordinary instrumentation and signals derived from a heat frequency oscillator (McIntosh Laboratories Model MC-60 power amplifier); at radio frequencies from 0.1 mega-cps to 50.0 mega-cps, capacitance unit characteristics were similarly investigated but with a special band switching amplifier as the signal source; at very-high frequency and ultra-high frequency ranges, from 50 mega-cps to 1000 mega-cps, Sierra Electronic Corporation Power generators provided the signal sources; in the microwave region, from 1000 mega-cps to 10,500 mcps, Litton Corporation magnetrons provided the energy source and auxiliary equipment was used to obtain the desired data.

Having obtained the basic characteristics of the capacitance units, the next step was to obtain the performance of these units in environments which were expected to prevail in models of protected squibs. For this purpose squib simulating set-ups were devised to test the performance of various test samples, as shown in block diagram form, Figs. 16 and 17. In these tests, the same signal sources and equipments are used to investigate the Current Protection ratio characteristics, as derived in Appendix B. Essentially, the squib simulating set-ups were small, partitioned, copper housings, the compartments were arranged to include a bridge wire element; the capacitance unit whose performance was to be learned; a line terminating resistor; and various toroidal coils, these latter linking main and branch circuit leads. Component layouts and partitioning of the set-ups were governed by the need to hold physical dimensions to a minimum, and also, to prevent interaction among instrumented circuits. A view of the interior of one of the squib simulating set-ups is shown in Photographs 7 and 8.

CURRENT PROTECTION RATIO MEASUREMENT ARRANGEMENT
(LOW AND MEDIUM RADIO FREQUENCIES)

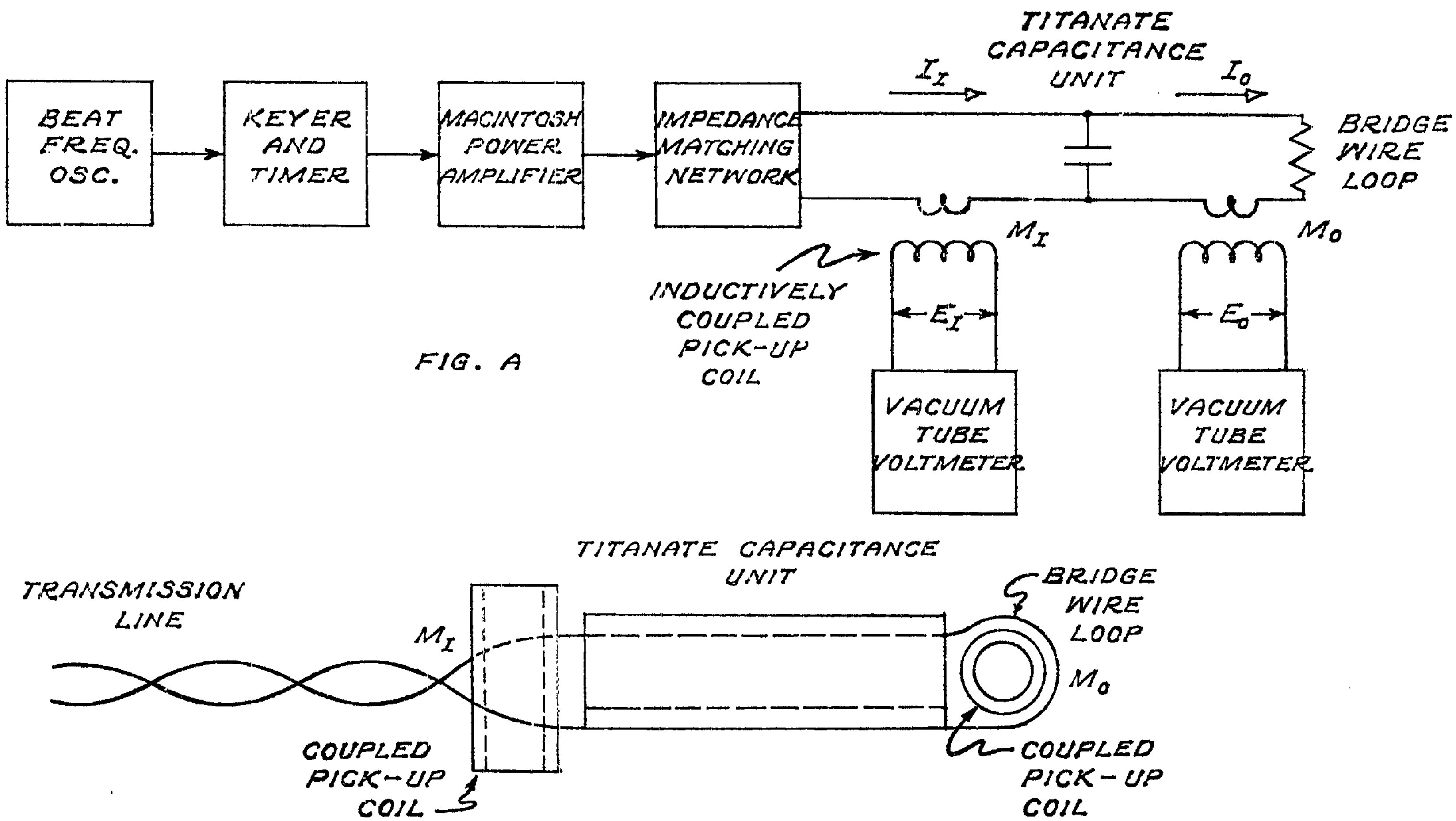
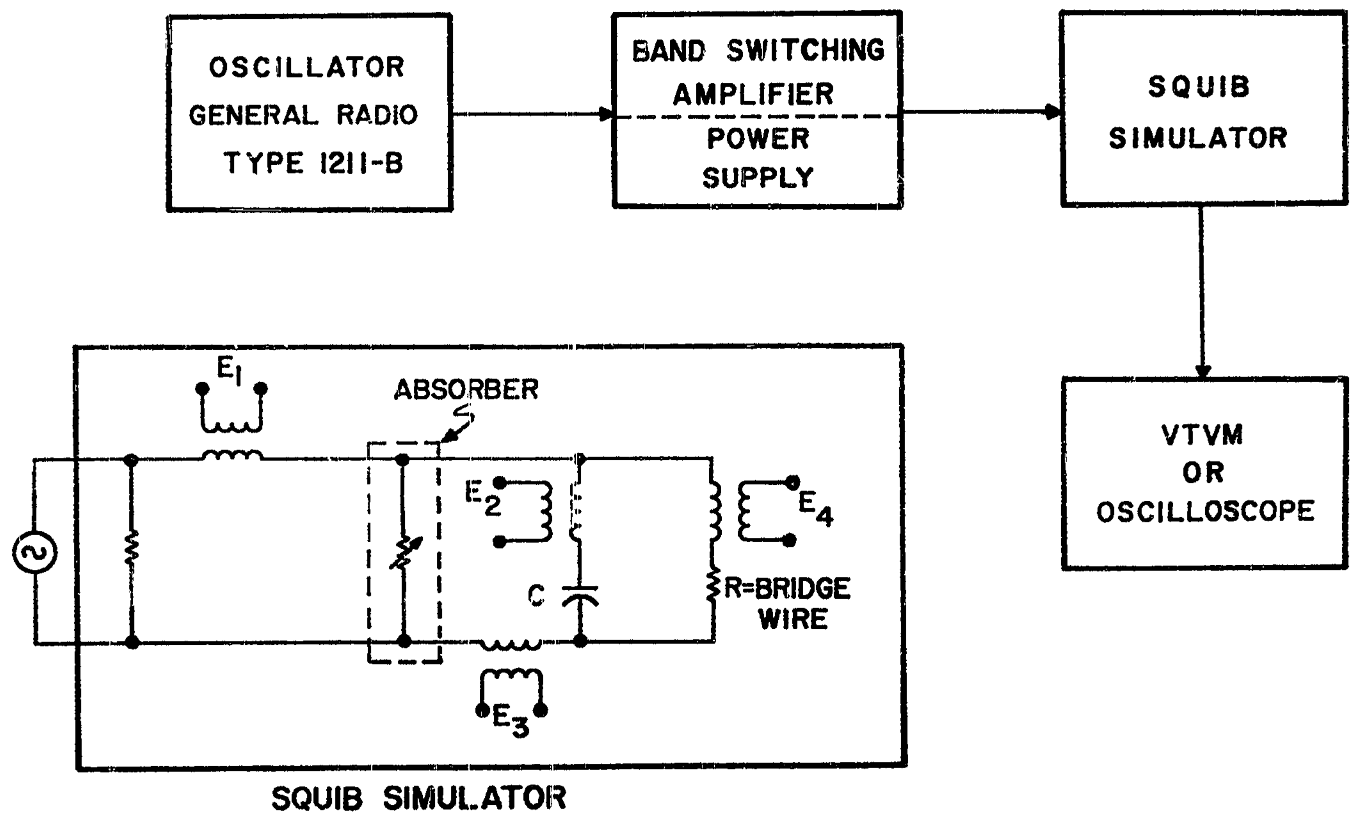
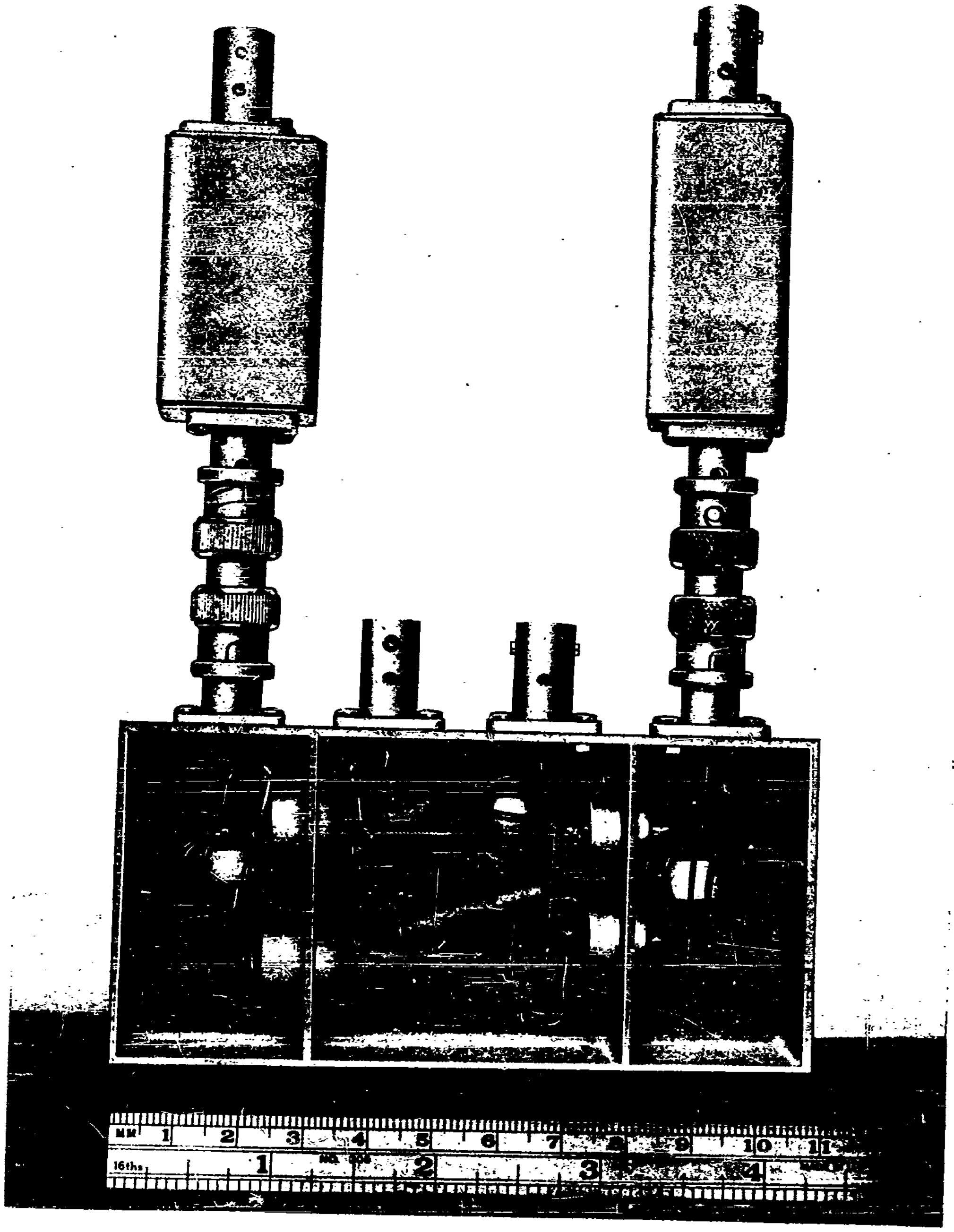


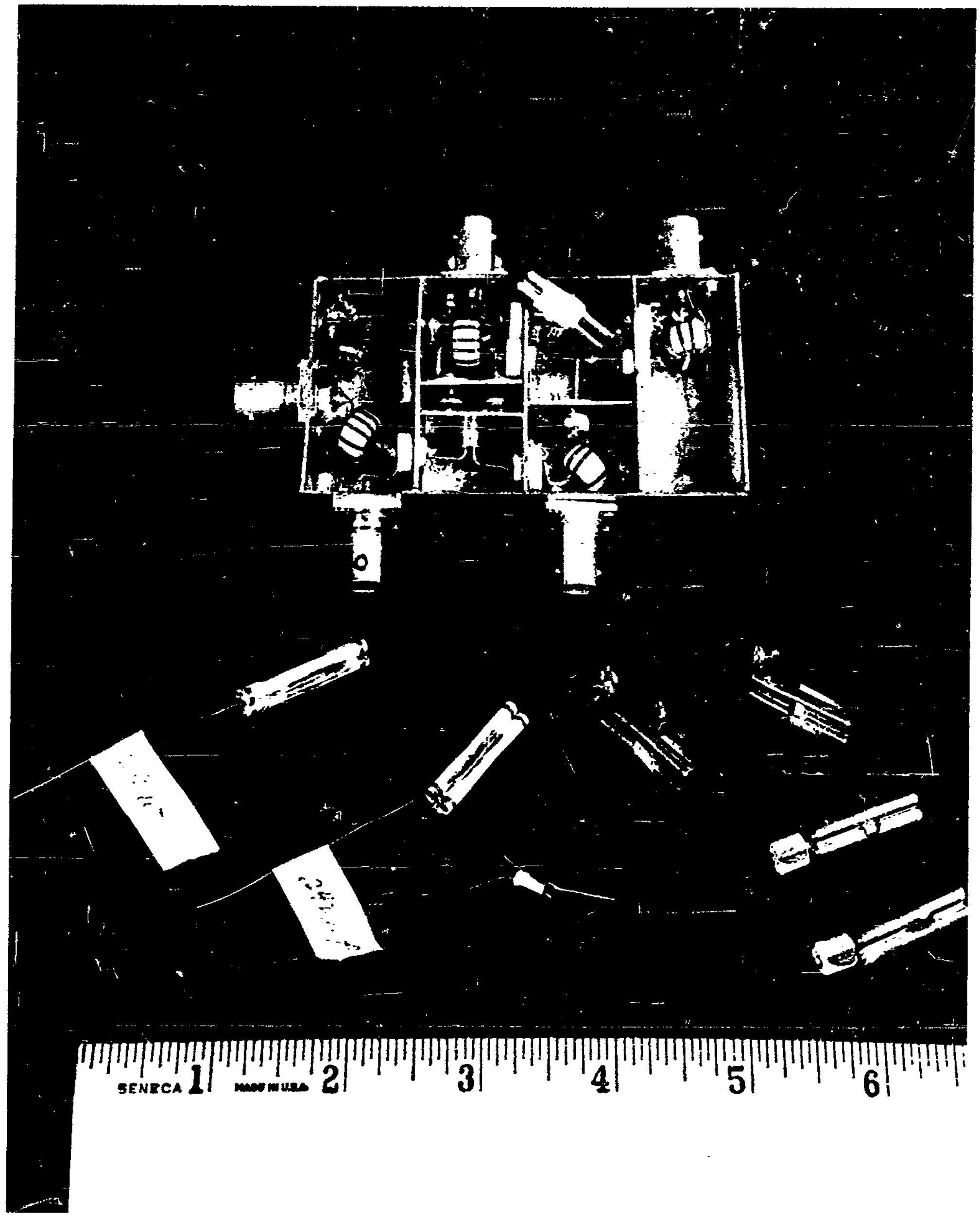
FIGURE 16



CURRENT PROTECTION RATIO BLOCK DIAGRAM USING SQUIB SIMULATOR.

FIGURE 17


MM 1 2 3 4 5 6 7 8 9 10 11
16ths 1 2 3 4



Photograph 8. Interior view of squib simulating set-up incorporating absorber, capacitor, and bridge wire elements together with samples of typical squib absorber and capacitance units.

Simulation set-ups varied somewhat in form for tests in several frequency ranges, but primary circuit parameters, except in a single instance, were kept practically the same. Most set-up changes, governed generally by instrumentation conditions, had to do with the numbers and sizes of housing partitions. The single case of alteration of circuit parameters occurred in the bridge wire branch. Normally, this was made up of about a one inch length of 0.002 inch diameter resistance wire (80% Nickel and 20% Chromium) supported on two short bushings. It was then characterized by a resistance of approximately 15.0 ohms, and an estimated self inductance, the estimate being based upon the physical dimensions of the branch, of 0.5 microhenry. In the excepted instance the bridge wire branch was made four inches long, and was coiled in part; having a resistance of 62.0 ohms. This modification was used to ascertain the effects of an increase in bridge wire branch impedance (see Fig. 18 and Table 11).

Coupled circuit techniques have been used to obtain branch current values. More specifically, these practices involved threading the leads bearing currents whose values were to be found through toroidal inductors. Further, the threading, which gave rise to the primary or inducing section of the coupled system, was arranged to have the effect of a single turn; the toroidal secondary sections, in order to develop sufficient voltage for indicating purposes at all frequencies, were made with varying turn numbers. Toroids, in other words, were changed with signal frequency bands, the toroids having the largest numbers of turns being used at the lowest frequencies and those having the fewest turns at the high frequencies. In all cases, however, toroid windings were operated under open circuit conditions. Instrumentation, accordingly, has been dependent upon the relationship

$$E = 2\pi f M I \tag{4.1}$$

where E denotes the voltage induced in the toroid windings; I signifies the value of the branch current which brings about voltage E, f is the frequency of I and E; and M is the mutual inductance between the branch lead and toroidal inductor.

Currents of most interest in a squib protected by reactive shunts are those which flow in the bridge wire and those which enter the squib. Accordingly, measurements of values of those currents was the aim of the instrumentation. To reduce the possibility of error additional current measurements were made occasionally in other circuit sections, but such measurements were of an ancillary nature. To illustrate the measurement technique employed let it be supposed that

CURRENT PROTECTION RATIO CHARACTERISTICS EXHIBITED BY TITANATE CAPACITANCE UNIT
(Samples from lot submitted by Erie Resistor Corporation on 10 January 1961)

Cluster of three (3) Cylindrical Titanate Units - Sample #2

$C = 0.52\ \mu f$ $R = 62\ \Omega$ $M = \frac{M_o}{M_I} = 0.57$

Freq(mc)	E_I	E_o	E_g	$\frac{I_I}{I_o}$	$\frac{I_g}{I_o}$	$N_{db} = 20 Log_{10}\left(\frac{I_I}{I_o}\right)$	$N_{db} = 20 Log_{10}\left(\frac{I_g}{I_o}\right)$
1	0.70	------	0.64	------	------	-----	-----
2	0.66	------	0.60	------	------	-----	-----
3	2.00	------	1.85	------	------	-----	-----
4	2.20	------	2.00	------	------	-----	-----
5	2.00	0.028	1.40	40.0	28.0	32.0	29.0
6	2.00	0.002	1.80	560.0	504.0	55.0	54.0
7	3.00	0.002	3.40	840.0	950.0	58.5	59.5
8	3.00	0.002	2.70	840.0	755.0	58.5	57.6
9	2.70	0.010	2.50	151.2	140.0	43.6	43.0
10	3.00	0.030	2.70	56.0	50.40	35.0	34.0
14	2.0	0.006	1.80	190.0	171.0	45.6	44.7
20	2.0	0.011	1.80	103.5	93.4	40.3	39.6
28	2.0	0.036	1.80	31.7	28.5	30.0	29.1
50	4.0	0.24	3.9	9.33	9.10	19.4	19.2[illegible]
60	5.6	1.4	4.9	2.24	1.96	7.0	5.0
70	6.0	0.52	5.4	2.40	5.81	7.6	15.3
80	4.9	0.69	5.5	3.97	4.46	12.0	13.0
100	4.5	0.8	6.0	3.15	4.20	10.0	12.4
120	8.4	1.45	9.5	3.24	3.66	10.2	11.3
130	12.5	16.5	4.5	0.42	0.15	-----	-----
140	3.9	2.0	2.5	1.09	0.70	0.75	-----
150	6.4	3.4	4.8	1.05	0.79	0.42	-----
160	3.8	2.1	1.35	1.01	0.36	-----	-----
200	5.4	0.85	5.4	3.55	3.55	11.0	11.0
250	5.0	5.5	6.3	0.50	0.64	-----	-----
300	4.2	7.4	7.6	0.31	0.57	-----	-----
350	2.2	5.9	5.9	0.20	0.56	-----	-----
400	1.0	5.9	5.3	0.09	0.50	-----	-----
500	0.38	2.7	3.0	0.07	0.62	-----	-----
550	0.64	1.85	2.7	0.19	0.81	-----	-----
600	0.55	0.66	1.35	0.46	1.14	-----	0.114
650	1.0	0.43	1.4	1.30	1.82	2.28	5.2
700	2.7	0.42	2.3	3.60	3.06	11.1	9.7
800	0.72	1.0	0.9	0.40	0.50	-----	-----
850	0.28	0.3	0.34	0.52	0.63	-----	-----
900	0.2	0.58	0.2	0.19	0.19	-----	-----
1000	0.09	0.62	1.75	0.08	1.58	-----	3.97

Table XI

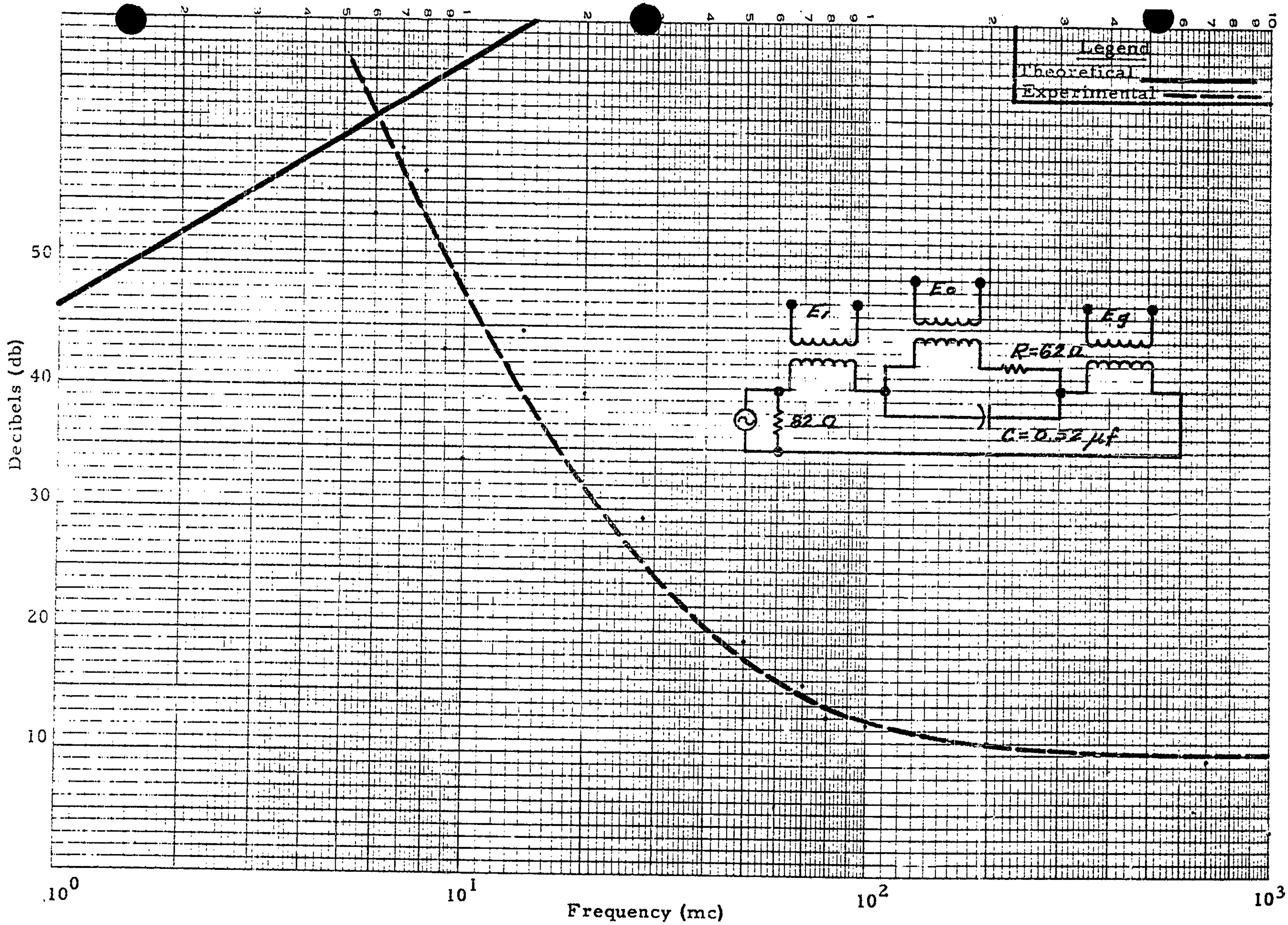


Fig. 18 - Current Protection Ratio Characteristics (Cluster of three (3) Cylindrical Titanate Units-Sample #2)
(Sample from lot submitted by Erie Resistor Corporation on 10 January 1961)

in a given set of circumstances the total current entering a protected squib has a value of I_I; that this current induces in a toroid, coupled by mutual inductance, M_I, to the line lead, a voltage E_I; and, similarly, that in the bridge wire branch a current of value I_O flows, which current, in turn, induces in a toroid, whose mutual coupling to the bridge wire amounts to M_O, a voltage E_C. Next assume these quantities are related functionally after the manner of equation 4.1. From comparison of the two ensuing relationships the line current to bridge wire current ratio may be formed, that is,

$$\frac{I_I}{I_0} = \frac{E_I M_0}{E_0 M_I} \tag{4.2}$$

To this, incidentally, has been given the name Current Protection Ratio. By taking the logarithms, to base 10, of the quotients in equation 4.2 they may be expressed in decibels. Written to conform to this concept they become

$$N_{DB} = 20 \log \frac{I_I}{I_0} = 20 \log \frac{E_I M_0}{E_0 M_I} \tag{4.3}$$

Current Protection Ratios represented graphically as functions of frequency served to illustrate the degree to which various capacitance unit samples provided protection to squibs. From such representations, too, the relative values of component parameters were estimated. In most analytical efforts of the latter kind, however activities were confined to the low frequency portion of the range used for study, that is, below about 5.0 mega-cps. At the higher frequencies, as was to be expected, squib circuit elements showed forth non-linear characteristics, and so provided little basis for desirable design changes. Over the low frequency span considered, actually just below the region where stray wiring capacitance effects came into play, reasonably good agreement could be obtained between results calculated from assumed equivalent circuits, representative of squib elements, and test data from squib simulating set-ups.

To provide enlightenment on both this last corroborative effort and the analytical process described it will be assumed that a squib circuit is comprised essentially of a bridge wire resistance R_B, and an imperfect capacitor in shunt therewith. Furthermore, this capacitor again will be supposed portrayable by two, paralleled circuit branches, the one including a perfect capacitor, C, in series with a resistance r and an industance L, while the second branch is made up solely of a resistance R.

If, now, this equivalent circuit representation of a squib is analyzed for the ratio of the total network current, denoted here as I_L, to that in the bridge wire branch, signified by I_B, it will be found that this quotient is given by

$$\frac{I_L}{I_B} = \left[\frac{R + R_B}{R}\right] \left\{\frac{LCp^2 + C\left[r + \frac{RR_B}{R + R_B}\right]p + 1}{LCp^2 + Crp + 1}\right\} \qquad (4.4)$$

Here the factor $p = j\omega$, where ω is the circular frequency and j denotes the imaginary operator $\sqrt{-1}$.

From this expression it is apparent that the low frequency point (first corner frequency) from which a capacitance unit commences to afford squib protection is determined by the magnitude of the time constant,

$$C\left[r + \frac{RR_B}{R + R_B}\right] \qquad (4.5)$$

and that the realizable insertion loss stemming from use of the unit is dependent largely upon the smallness of the time constant Cr. Resistance r, it may be noteworthy was found to have values ranging from 0.1 ohm to about 5.0 ohms; generally, on the other hand, resistance R varied from approximately 100.0 megohms to 0.5 megohm in the case of conventional barium titanate body capacitors, and from a few thousand ohms to about 50.0 ohms in the case of capacitors having dielectric constants of the order of 100,000.

Forms taken by Current Protection Ratio characteristics may be inferred from equation 4.4 when specific values of the parameters are substituted therein. As a consequence of such a step it would be found that the quadratic term in the numerator yields two real roots, whereas the corresponding term in the denominator may have either real or complex roots, the type being dependent upon electrical properties of the subject capacitance unit samples. What is more the numerator quadratic roots are determinative of a large valued time constant and a small valued one. Cognate periods of the demoninator quadratic are intermediate to those of the numerator. It follows, therefore, that a representative Current Protection Ratio characteristic would start as a function independent of frequency; would rise at essentially a +6.0 decibel per octave

rate from the corner frequency associated with the high valued time constant in the numerator; would change its rate of rise over a frequency range determined by the nature of the denominator quadratic, rising or leveling off initially but ultimately progressing toward a -6.0 decibel per octave rate; and, finally, at a frequency determined by the low valued time constant of the numerator, would assume again a level locus. On the graphical representations of Current Protection Ratio characteristics which were obtained with various capacitance unit samples, there is included a +6.0 decibel per octave asymptote which passes through the corner frequency point defined by the time constant CR_B, which is shown in Section IVC(3)a.

In order to justify the use of capacitance units to insensitize electroexplosive matches from R-F influences, another area had to be extensively investigated.

This investigation, impedance measurement, was to include all the circuit elements which would be fabricated into the laboratory model of the squib assembly. It was necessary to determine what sort of characteristics were exhibited by the circuit elements by themselves and also when they were paralled together, as would be the case in an actual squib environment.

It was assumed that the squib bridge wire would appear as a pure resistive component at low frequencies up to approximately 1.0 mega-cps; and then as the frequency was increased still further, the the impedance would take on slowly increasing values of resistive and inductive reactance components up through 1000 mega-cps. Above 1000 mega-cps values of resistance would increase still further, but erratically, and the reactance component would turn conductive. These assumptions were later verified in the impedance measurements shown in Section II, Fig. 3.

The capacitance units were assumed to act as a pure capacitive reactance from low frequencies up to approximately 1-10 mega-cps. Somewhere in this region the capacitor changes its reactive component due to the lead length and then turns inductive. The inductive reactance component increases smoothly over a wide frequency range to approximately 1000 mega-cps, and then, once again turns capacitive.

The impedance measurement of representative capacitor samples tend to support these assumptions.

The next step was to put the two elements together in parallel as they would appear in the actual squib environment. Again, we assumed

that they would act as a composite impedance of the two circuit elements alone. It was necessary that the impedance combination would have at low frequencies varying values of resistive and capacitive components. As the frequency increases beyond 1-10 mega-cps, the parallel combination of R and C should change its characteristics to appear inductive. Throughout these higher frequencies, 1-10 mega-cps through approximately 800 - 1000 mega-cps, the values of resistance should remain low and the inductive reactance component should slowly increase with increasing frequency. When the microwave region is approached the combination should then change its reactance component to become capacitive again. These assumptions were later proved to be true as will be shown in Section C(3)a of this report.

Additional impedance measurements of the circuit elements, such as, the hermetic seal, increased the effectiveness of the arrangements in the complete squib assembly. Measurements of these elements and their combination with other circuit elements are shown in the data runs in Section IVC(3)a.

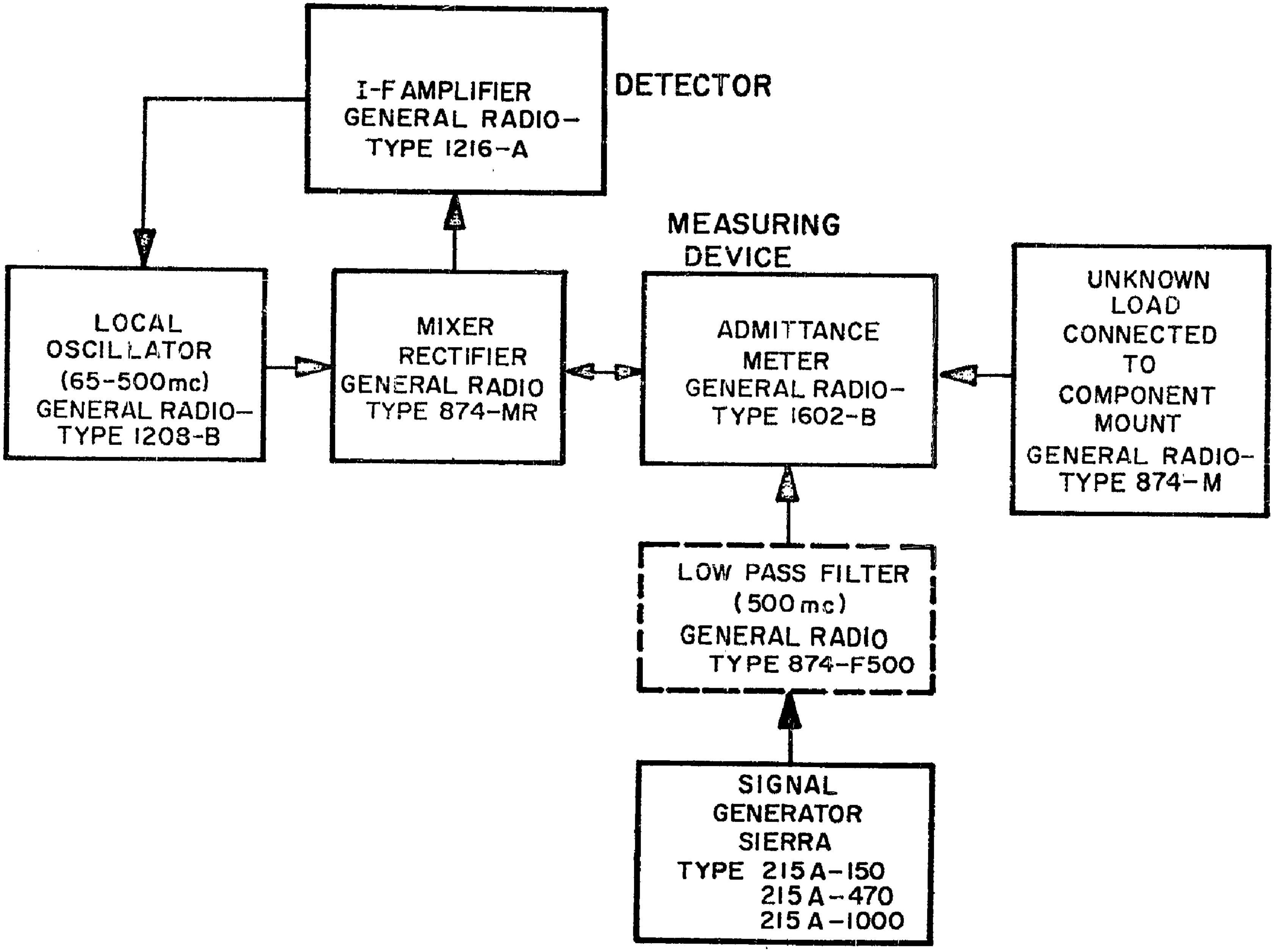
Block Diagram, Fig. 19, illustrates the apparatus set-up which was used to obtain the data from 50 mega-cps to 1500 mega-cps.

The next necessary step was to fabricate from readily available equipment (eg. brass ferrule) laboratory test model squib assemblies in order to scrutinize more closely the behavior of the completely assembled device over the specified frequency spectrum. A section of the appendix F describes the complete squib assembly in more detail.

Extreme care was taken with the lower portion of the ferrule casing to insure that it would sever upon detonation due to the decrease in its tensile strength and so reduce the axial reaction. Photograph 9 shows an exploded view of the complete squib assembly.

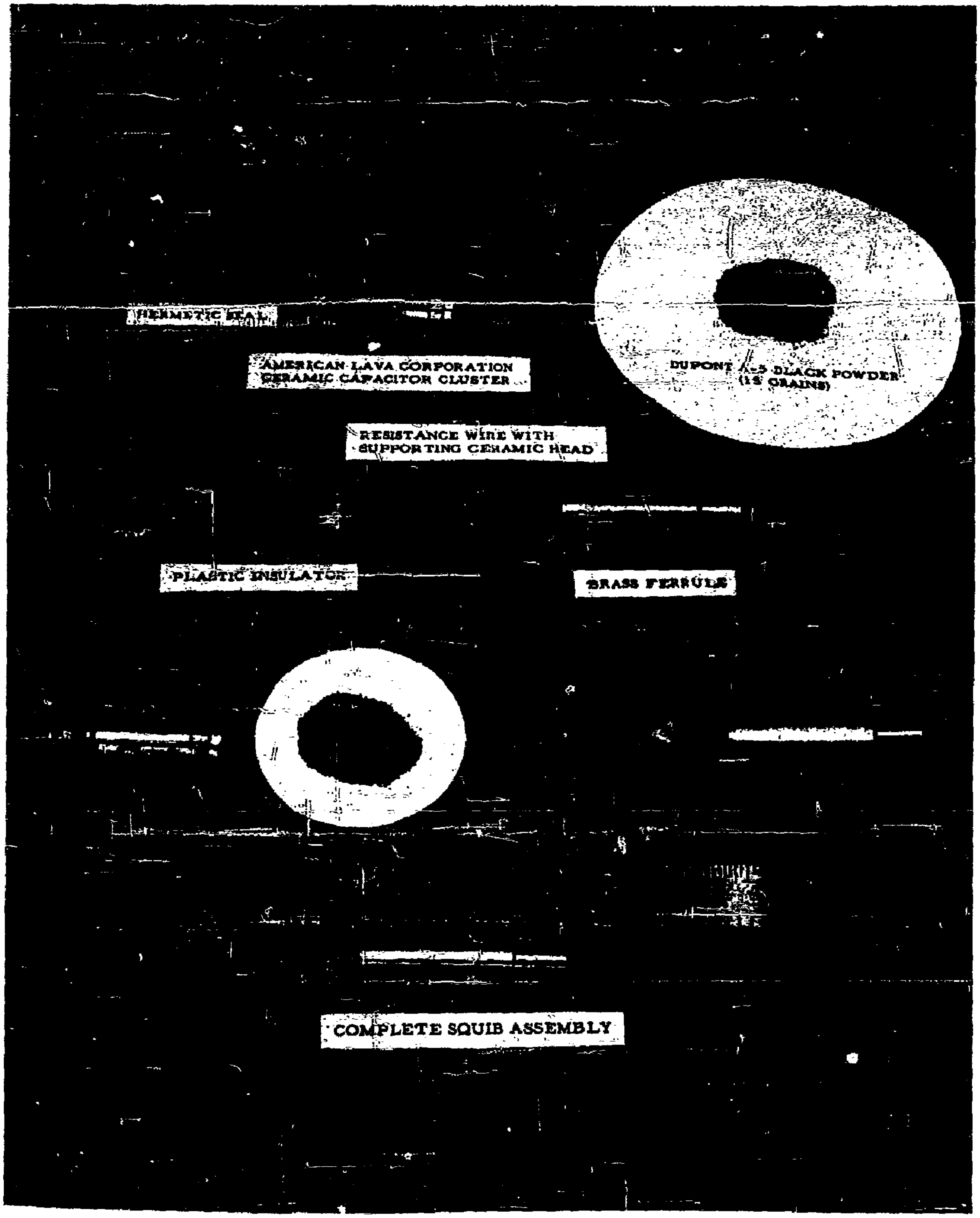
Since it was an impossible task to make measurements of the branch currents within the assembled devices, laboratory test methods had to be devised to compare the effectiveness of a protected squib assembly to that of an unprotected squib assembly.

At the low frequencies (50c - 160KC) direct measurements could accurately be obtained. These measurements were of current entering the squib assembly input terminals. (Refer to Figure 20). For the purpose of collecting data as the frequency was increased above 160KC, as accurately as possible, a dual monitoring set-up was used to as high a frequency as instrumentation would permit. This dual system consisted

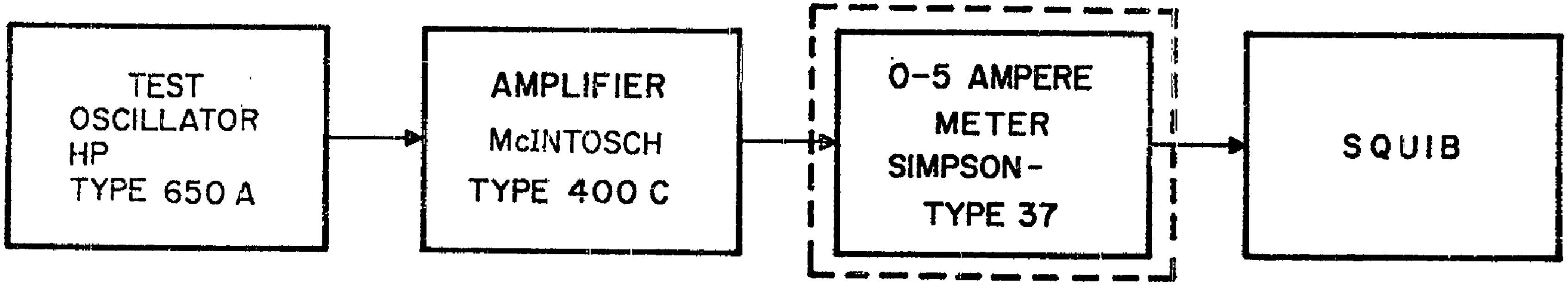


50mc–1500mc IMPEDANCE MEASUREMENTS BLOCK DIAGRAM.

FIGURE 19



Photograph 9. View of squib elements, exploded view of squib, and complete squib assembly.



50c — 160kc CURRENT PROTECTION RATIO MEASUREMENT BLOCK DIAGRAM

FIGURE 20

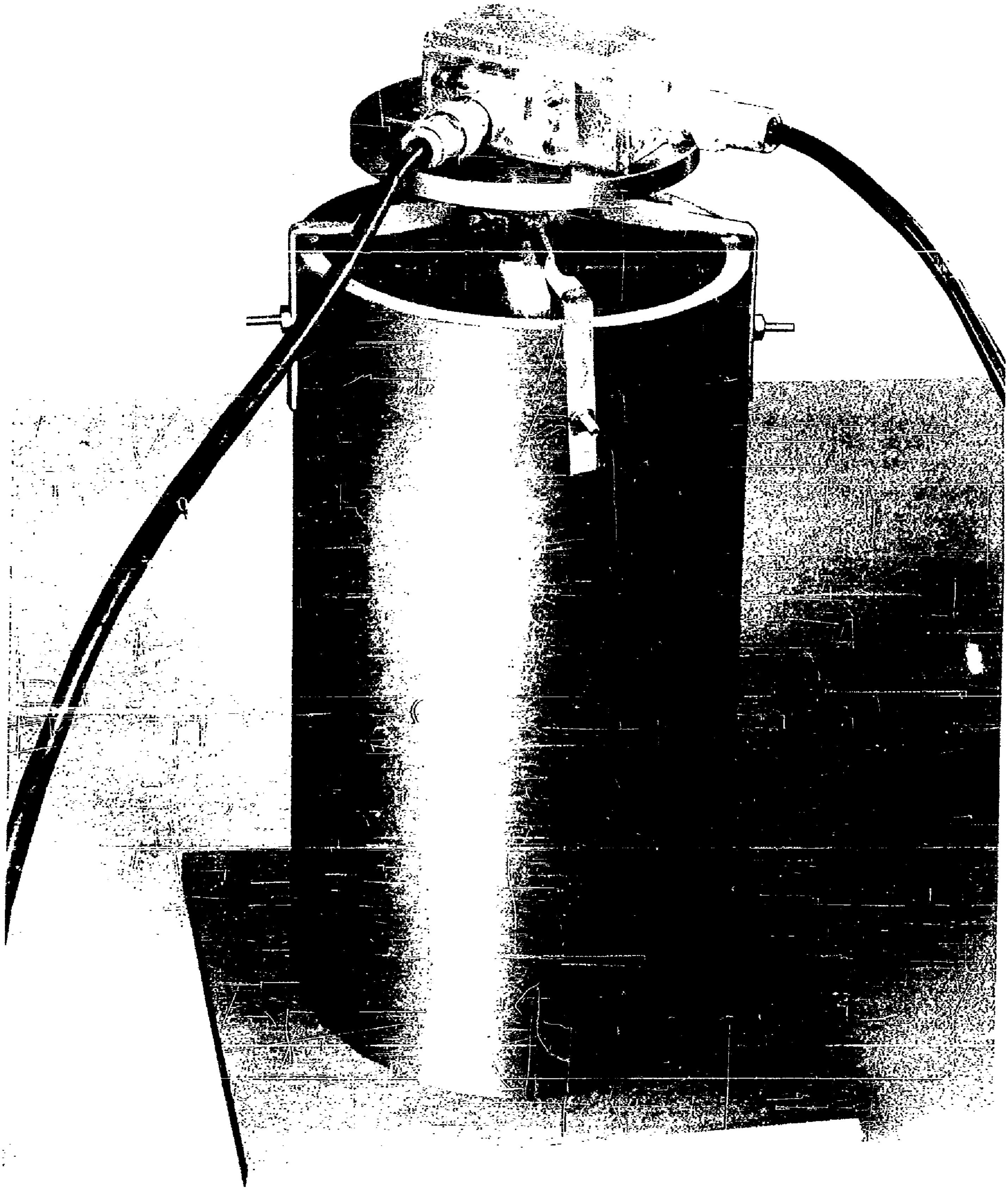
of an RF ammeter to measure the line current and a detector, shown in Photograph 10. The detector was designed and constructed to measure the current flow indirectly by means of induced voltages. (This method ix similar to that which was discussed previously in this section). The only variation in this case is that a double toroidal shaped pick-up coil is used around an open line which terminates at the squib input terminals and that the RF voltage induced in the coil is rectified by a series diode. (Refer to Figures 21 and 22.)

The mount on which the detector is fastened functions as a protective element from shock due to squib detonations and as a squib assembly holder.

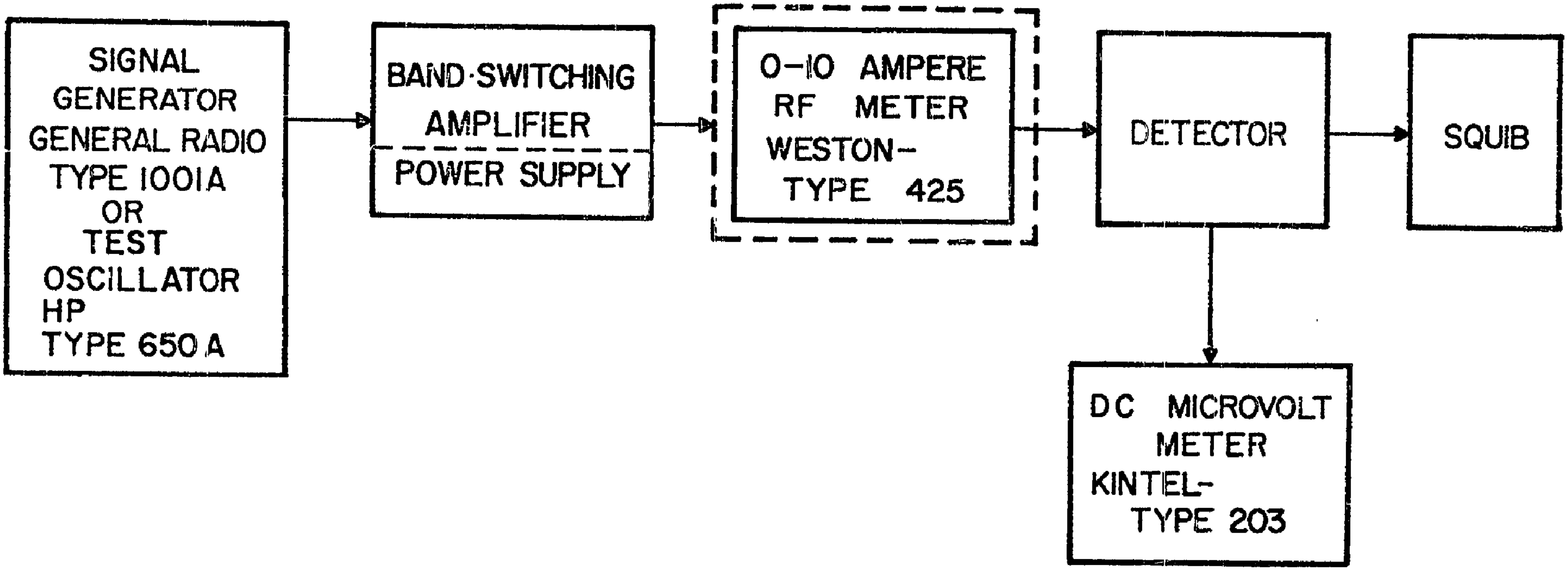
The detector calibration curve was devised, next, in order to obtain values of current flow above 20 mega-cps The ordinate of the curve is expressed in d-c volts per ampere, while the abscissa is expressed in frequency. In this manner, when the RF ammeter produced discontinuities in the line (above 50 mega-cps) which warranted its removal; the detector, just described was used alone from this point out to the microwave region.

Making use of this instrumentation, tests were conducted to ascertain the minimum current protection ratio which could be achieved with a protected complete squib assembly versus an unprotected complete squib assembly. This information is shown in a histographic representation form in Section IVC(3)a of this section. At various frequencies throughout the spectrum these measurements were recorded for laboratory test model comelete squib assemblies fabricated with one or two turns of bridge wire in parallel with the Erie Resistor or American Lava production model capacitance assemblies. The complete squib assembly was the line termination for all tests for a time duration of thirty (30) seconds. At each measurement interval a minimum of two complete squib assemblies per type were used.

In the microwave frequency spectrum it is difficult to measure voltages and currents on a transmission line with any usable degree of accuracy. In this frequency range only relative values of voltage and current can be measured. Although such a procedure may tell us relatively little of what actually goes on inside a microwave component, it may tell us a great deal about its behavior when viewed from the terminals of a component under study In some instances, the comparison may be approximate, but in others it is very accurate indeed. In most cases, an over-all view is not only sufficient but its use may actually be advantageous for it allows us to by-pass certain minutiae of detail and

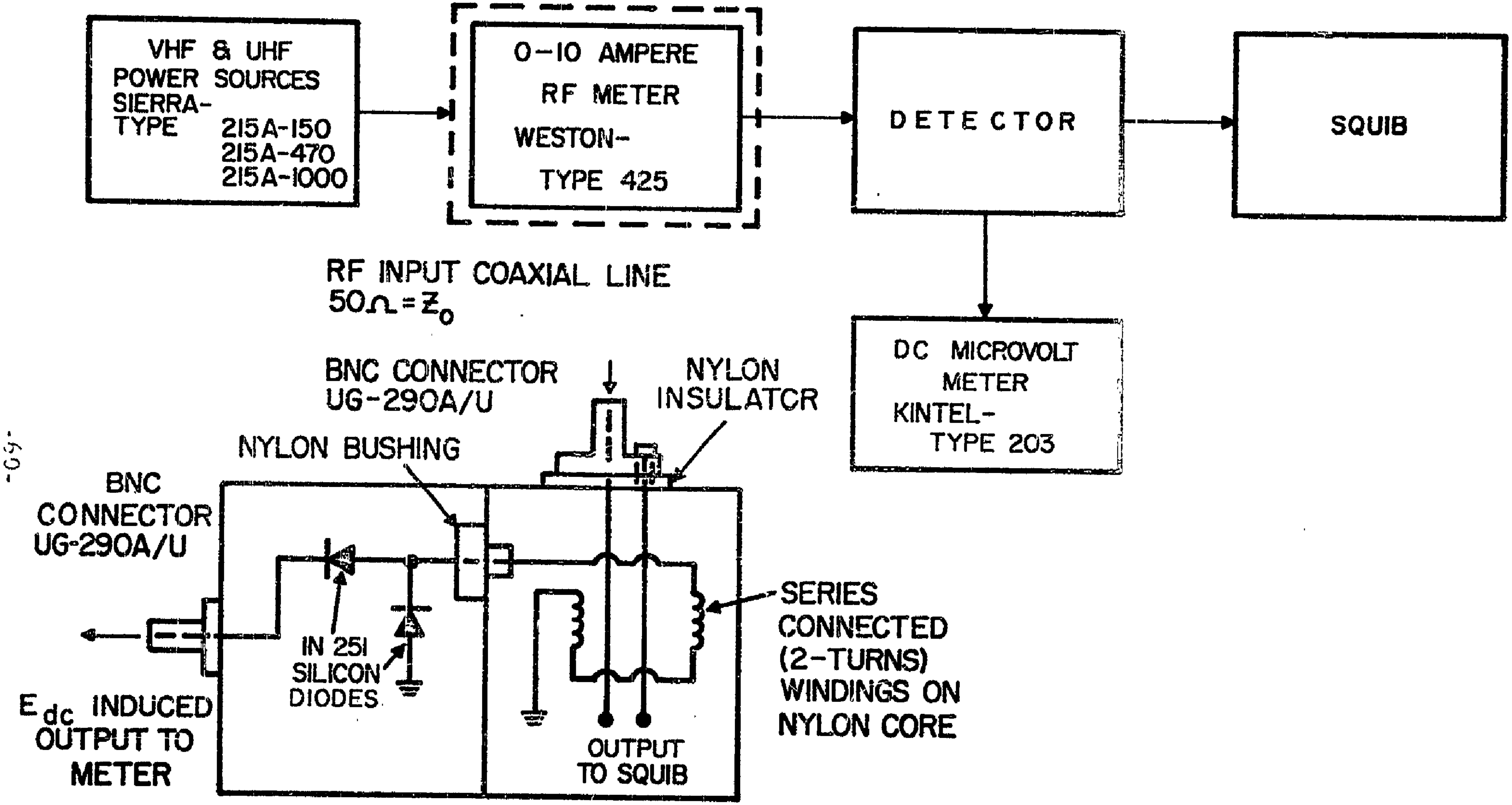


Photograph 10. View of squib detonating chamber, mounting block and detector.



200 kc—50 mc CURRENT PROTECTION RATIO MEASUREMENT BLOCK DIAGRAM.

FIGURE 21



50mc–1000mc CURRENT PROTECTION RATIO MEASUREMENT BLOCK DIAGRAM.

FIGURE 22

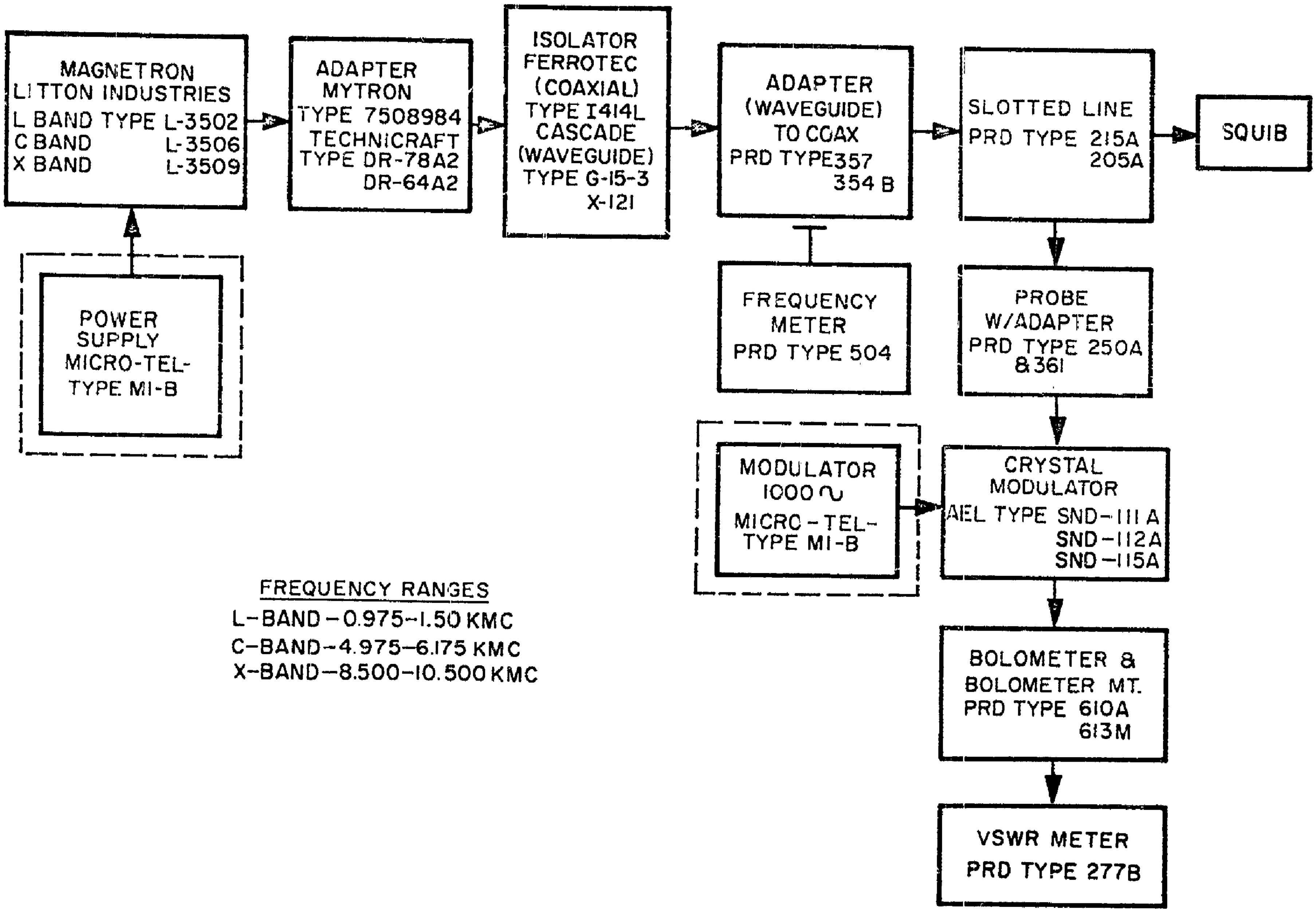
arrive at a result that is accurate as well as easily interpreted in terms of common electrical experience.

To accurately determine branch currents and voltages of each branch of a squib's internal circuits is next to impossible since electrical measurements reveal only the resultant of all intrinsic parameters. Such annoyances as fringing fields and resonance between discontinuities can give rise to rather large errors.

Actually in practice, the only observable quantity is the reflection coefficient (or VSWR). A study of the behavior of the reflection coefficient as such provides all the information that really counts.

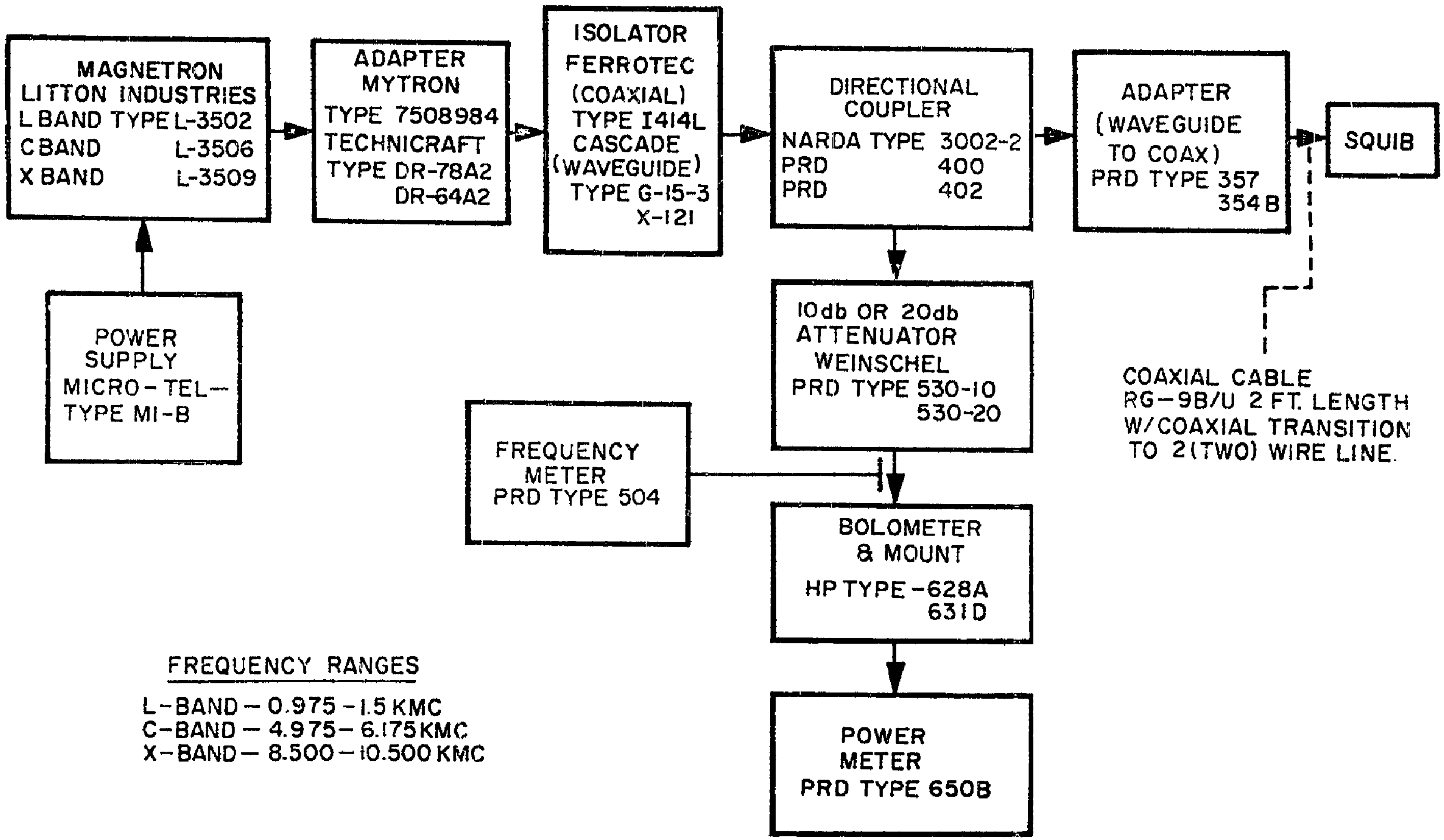
Since the voltage standing wave ratio is given by VSWR $= \frac{1 + |K|}{1 - |K|}$ (where $|K|$ is the voltage reflection coefficient) the amplitude and angle of reflection coefficient can be determined with the use of a Smith Chart, by measuring the ratio of maximum electric field value to minimum electric field value and measuring the distance from a reference plane (shorted line) to where such maxima and minima occur. To obtain the power reflection coefficient $|K|$ is squared, thus $1 - |K|^2$ is the coefficient of power absorbed by the squib. By measuring the incident r-f power upon the squib, the power reflected can be determined as well as the power absorbed by the squib for various r-f power levels.

For measurement of voltage standing wave ratio or angle of reflection coefficient, the test set-up shown in Fig. 23 was used. Figure 24 is the test set-up used in compiling data of the r-f power handling ability of the squibs.



MICROWAVE VSWR MEASUREMENT BLOCK DIAGRAM.

FIGURE 23



MICROWAVE POWER MEASUREMENT BLOCK DIAGRAM.

FIGURE 24

C.2. Data Presentation Techniques

In order to determine the degree of insensitation to R.F. energy imparted to squibs by capacitance units, a large volume of data was collected, requiring a simple and straightforward manner of presentation in order to provide the greatest amount of information about the device under test. In order to accomplish this, four methods have been chosen to present the accumulated data. They are: (a) Current Protection Ratio Characteristics, (b) Histographic Representation, (c) Smith Charts, and (d) VSWR versus Frequency Charts.

The current protection ratio data is presented by a current ratio, expressed in decibels, plotted versus frequency. This graph, an example of which is shown in Figure 25, provides a simple method of quickly determining the exact amount of protection provided by the capacitance unit at a frequency of interest. The derivation of the current protection ratio formula is included in Appendix B.

An example of the histographic representation of the effectiveness of capacitance units is shown in Figs.52-53. In this figure is a plot of current protection, in decibels, versus frequency. Here, the decibel ratio indicates the minimum amount of protection obtainable, and is referred to a level of 0.3 amperes of direct current. The derivation for this current protection ratio is in Appendix B.

A typical Smith Chart diagram is shown in Figure 28. For an explanation of the Smith Chart and its application to impedance measurements, reference is made to (7) and (8) in the Bibliography. The Smith Chart method of data presentation was chosen for the reason that information other than impedance data may be readily obtained on a graphical basis. Examples are, voltage standing wave ratio, transmission loss, reflection coefficient and reflection loss.

A typical graph of voltage standing wave ratio versus frequency is shown in Figure 62. In this figure is shown the magnitude of mismatch produced by an electro-explosive match terminating a transmission line. This form of presentation was chosen in order to present only the degree of mismatch produced by the squib over a wide frequency range.

3. Sample Data Runs

a. <u>100 KC to 1000 MC</u>

Shown in Figs. 34 and 35 and Tables XXII and XXIII are impedance measurements vs. frequency of representative samples of Erie Resistor Corporation capacitance assemblies with a bridge wire of one and two turns, and a hermetic seal attached to the parallel combination. Impedance versus frequency charts are shown in Figs. 36 and 37, Tables XXIV, XXV, which incorporates the complete squib assembly as shown in Photograph 9, these contain the capacitance assembly, bridge wire with lead styphnate, ceramic mount, hermetic seal, vinyl tubing for insulation, and a brass ferrule. Impedance versus Frequency Charts, Figs. 38, 39, 40 and 41, Tables XXVI - XXIV illustrate the changes in impedance due to decreases in explosive powder content in the complete squib assembly.

Figure 42, Table XXX, shows the inductive and capacitive reactance components of impedance vs. frequency of an American Lava Corporation production model capacitance assembly with the bridge wire in parallel across it (one and two turns). Measurements were recorded in Figs. 45 and 46, Tables XXXIII, XXXIV, which illustrates representative impedance values versus frequency of complete squib assemblies incorporating the American Lava Corporation capacitance assembly, with a bridge wire (one or two turns), lead styphnate bead mix, insulating vinyl tubing, hermetic seal, and brass ferrule. Figs. 47, 48, 49, and 50, Tables XXV - XXXVIII, illustrate the impedance measurements versus frequency of the complete squib assembly with variations in the number of turns of bridge wire (one or two turns) and explosive powder content.

Shown in Figure 51 is the detector calibration curve which was used for the purpose of obtaining the minimum current protection ratio exhibited by complete squib assemblies which incorporated American Lava and Erie Resistor Corporation capacitance assemblies. The histographic representations, are shown in Figs. 52 and 53, Tables XXXIX - XLII, illustrate minimum Current Protection Ratio in decibels versus frequency.

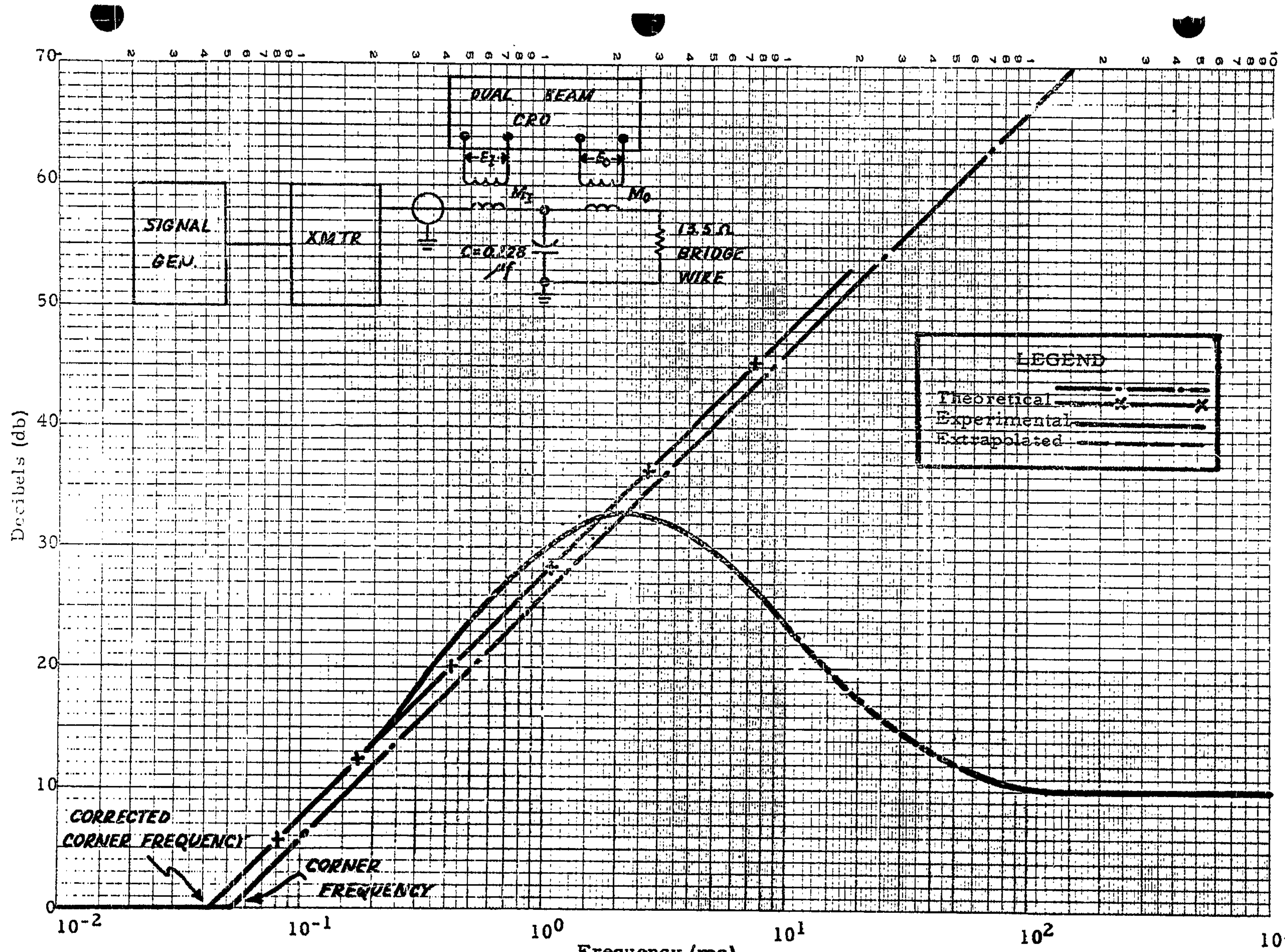


Fig. 25 Current Protection Ratio Characteristics (Parallel Plate Titanate Capacitance Unit - Sample 2)
(Samples from lot submitted by American Lava Corporation on 14 October 1960)

CURRENT PROTECTION RATIO CHARACTERISTICS EXHIBITED BY TITANATE CAPACITANCE UNIT

(Samples from lot submitted by American Lava Corporation on 4 November 1960)

Disc type Titanate Unit - Sample 1 Experimental Data

$C = 0.184\mu f \quad {}^{*}R = 14\Omega; \quad R = 130; \quad M = \frac{M_o}{M_I} = 0.57$

Freq(mc)	E_I	E_g	E_o	$\frac{I_I}{I_o}$	$\frac{I_g}{I_o}$	$N_{db}=20Log_{10}\left(\frac{I_I}{I_o}\right)$	$N_{db}=20Log_{10}\left(\frac{I_g}{I_o}\right)$
*13	5.2	4.0	0.40	7.41	5.70	17.40	15.10
*14	5.5	5.0	0.37	8.47	7.71	18.55	17.72
*17	3.0	2.9	0.40	4.2[illegible]	4.14	12.65	12.32
*20	6.6	6.0	0.48	7.84	7.12	18.90	17.08
*23	6.1	5.6	0.60	5.8[illegible]	5.32	15.30	14.50
*28	2.8	2.7	0.40	4.00	4.00	12.00	12.00
*31	2.6	2.4	0.40	3.71	3.42	11.40	10.68
*35	2.8	2.7	0.40	4.00	4.00	12.00	12.00
*40	5.0	4.6	0.40	7.12	6.55	17.10	16.32
85	5.2	5.6	0.60	4.95	5.32	13.90	15.30
90	5.0	5.6	0.58	4.91	5.70	13.82	15.10
100	5.0	6.4	0.55	5.18	6.62	14.28	16.40
110	5.0	8.8	0.48	5.94	10.55	15.50	20.40
120	7.4	60.0	1.40	3.01	2.42	9.60	7.68
130	60.0	10.0	10.00	3.42	0.57	10.70	-----
140	10.0	3.8	0.70	8.15	3.10	18.20	9.80
150	8.0	4.0	0.40	11.40	5.70	21.20	13.82
160	5.0	5.8	0.58	4.91	5.70	13.82	13.82
180	10.0	6.0	0.24	2.38	14.50	7.55	23.20
200	8.0	5.4	0.44	1.04	7.60	3.40	16.90
225	8.0	6.0	0.40	1.14	8.55	1.14	18.64
250	6.0	4.4	0.44	0.78	5.70	-----	13.82
275	6.0	4.2	0.70	4.89	3.42	13.80	10.68
300	6.0	4.3	0.80	4.27	3.06	12.60	9:70
350	6.0	5.8	1.70	2.01	1.95	6.60	5.80
400	4.0	7.0	1.80	1.27	2.22	2.08	6.92
450	6.0	8.0	3.40	1.01	1.34	0.08	2.54
470	0.57	3.4	0.90	0.36	2.15	-----	6.66
500	0.18	3.2	1.30	0.79	1.40	-----	2.92
550	0.21	2.5	1.00	0.12	1.43	-----	2.90
600	0.92	3.4	0.88	0.60	2.20	-----	6.90
650	1.20	2.6	0.72	0.95	2.06	-----	6.16
700	1.70	2.4	0.54	1.80	2.54	5.12	4.24
750	2.40	3.4	0.50	2.74	3.87	8.84	11.74
800	11.00	4.8	0.32	19.60	8.55	25.80	18.60
850	3.00	0.32	0.40	4.27	0.46	12.60	-----
900	2.20	1.6	0.33	3.80	2.74	11.60	8.72
950	1.50	7.4	0.67	1.23	6.30	1.80	16.00
1000	0.80	17.0	1.00	0.46	9.68	-----	19.42

Table XII

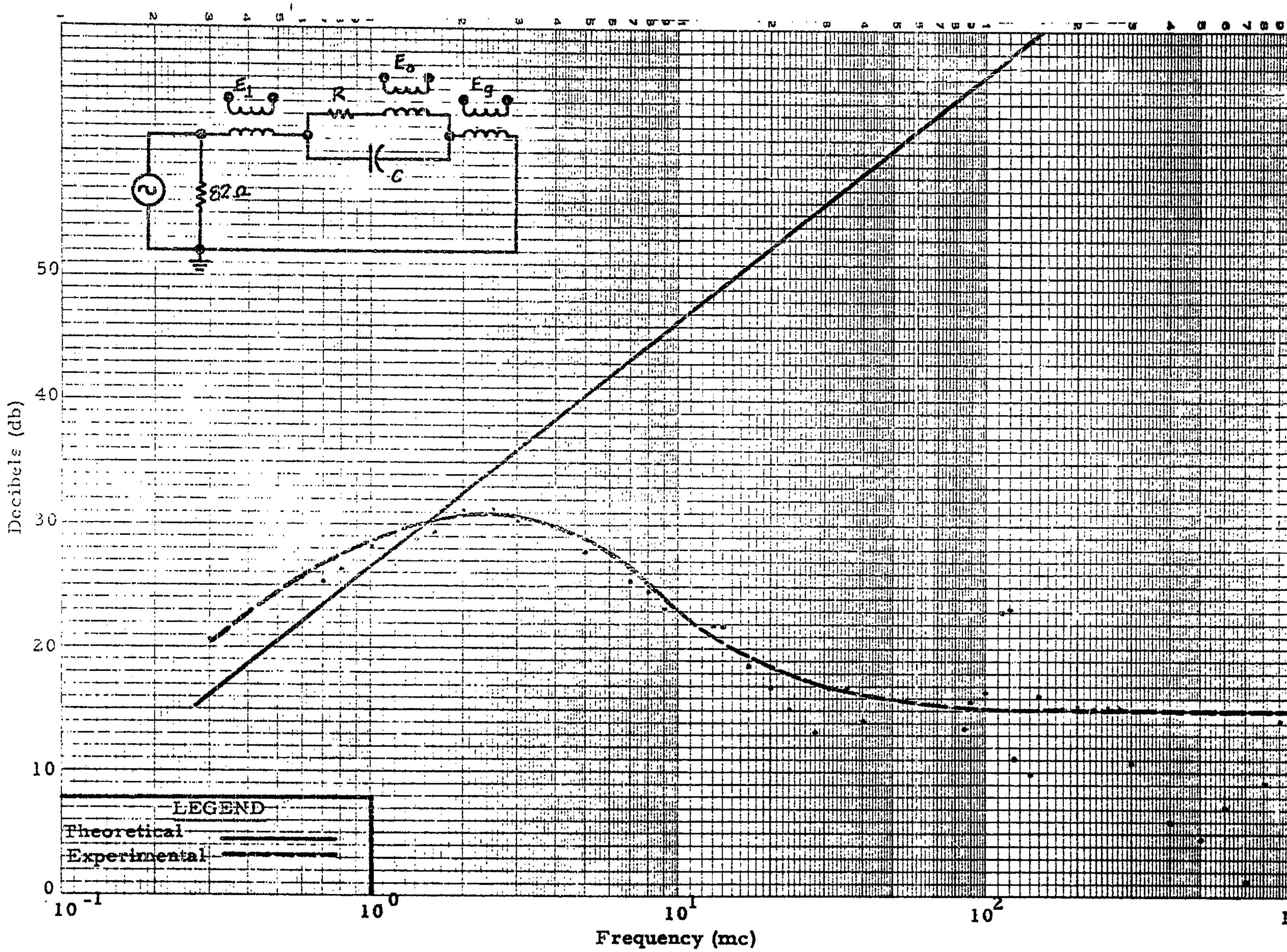


Fig. 26 Current Protection Ratio Characteristics - Sample #1
(Sample from lot submitted by American Lava Corporation on 4 November 1960)

CURRENT PROTECTION RATIO CHARACTERISTICS EXHIBITED BY TITANATE CAPACITANCE UNIT

(Sample from lot submitted by American Lava Corporation on 6 March 1961)

Cluster of Three (3) Cylindrical Titanate Units - Sample #8

$C = 0.235\ \mu f$ $R = 13.0\ \Omega$ $M = 0.76$

Freq(mc)	E_o	E_g	$\frac{E_g}{E_o} \times M = \frac{I_g}{I_o}$	$N_{db} = 20 \log_{10}\left(\frac{I_g}{I_o}\right)$
2	0.004	0.98	187.0	45.5
3	0.002	1.10	418.0	52.4
4	0.014	1.92	104.0	40.3
5	0.025	1.92	58.5	35.4
6	0.038	1.95	39.0	31.8
8	0.062	1.92	23.6	27.5
10	0.082	1.95	18.1	25.2
14	0.218	2.86	13.1	22.4
17	0.220	2.87	9.9	19.9
23	0.33	2.85	6.8	16.65
28	0.36	2.65	5.6	15.00
34	1.00	4.60	3.5	10.90
39	0.72	4.70	4.96	13.91
50	0.63	3.80	4.59	13.23
60	0.60	3.50	4.44	12.95
70	0.51	3.50	5.21	14.34
90	0.49	3.20	4.96	13.91
100	0.42	3.00	5.43	14.70
120	0.10	1.90	14.40	23.20
150	0.95	3.80	3.04	9.66
200	0.58	3.90	5.10	14.15
250	0.22	3.60	12.40	21.90
300	0.14	2.00	10.85	20.70
350	0.46	1.40	2.31	7.27
400	0.83	1.30	1.19	1.51
450	1.40	0.79	0.43	-----
500	0.90	0.10	0.09	-----
550	1.5	0.08	0.04	-----
600	3.4	0.96	0.21	-----
650	2.2	1.40	0.48	-----
700	0.8	0.64	0.61	-----
750	2.2	2.60	0.89	-----
800	1.3	5.00	2.92	9.3
850	2.2	2.00	0.69	-----
900	2.5	2.50	0.76	-----
1000	0.7	0.70	0.76	-----

Table XIII

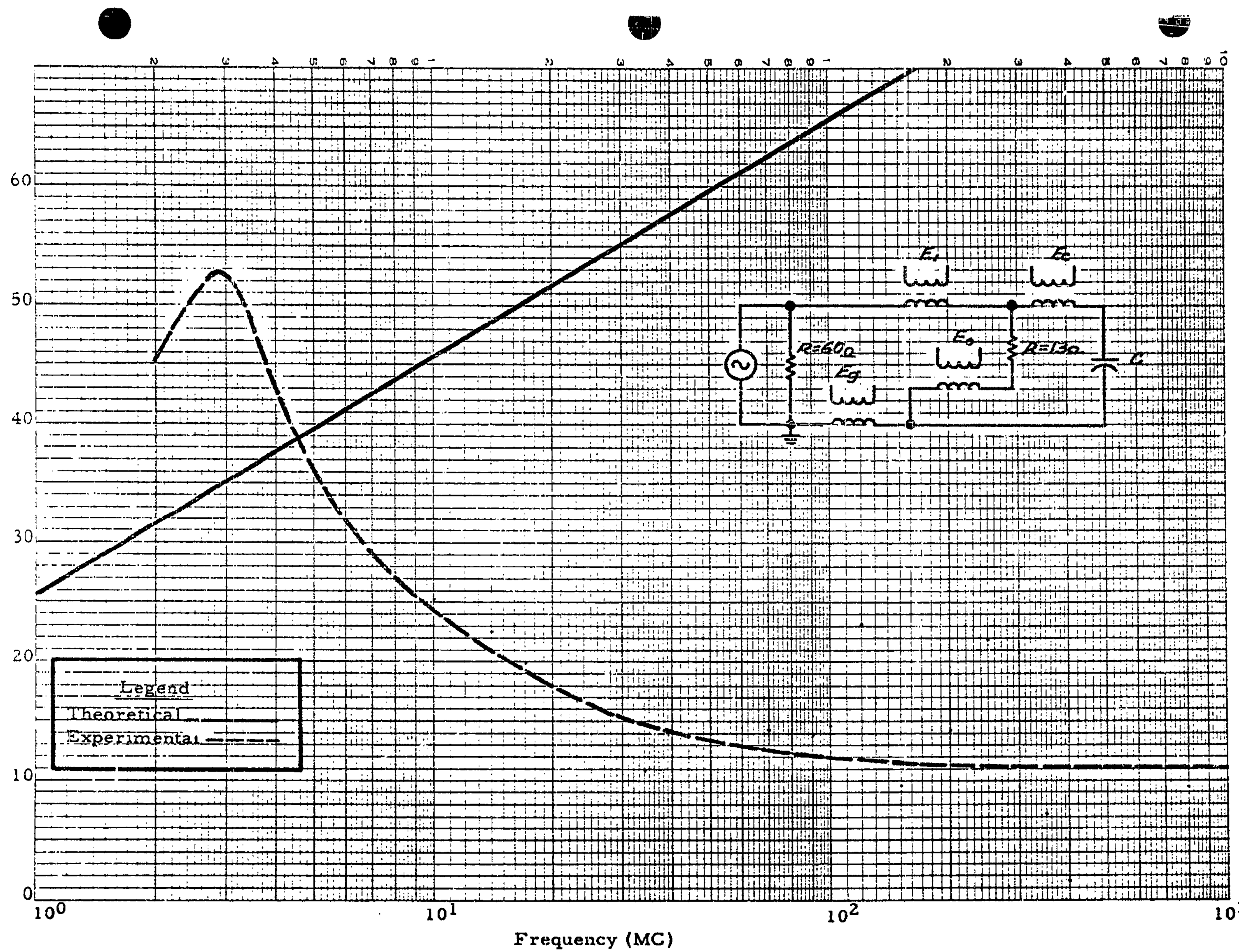


Fig. 27- Current Protection Ratio Characteristics (Cluster of Three (3) Cylindrical Titanate Units-Sample #8)
(Sample from lot submitted by American Lava Corporation on 6 March 1961)

Impedance Measurements at Various Frequencies Using Complete Squib Assembly. Ferrule w/polystyrene seal, Erie Resistor Corporation Titanate Capacitance Assembly (Cluster of three (3) Units).

$C = 0.53\ \mu f$ $\quad$ $R = 29.0\ \Omega$ $\quad$ Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No.	Z_R (Ω)
50	1	0 + j 11.87
100	2	0 + j 22.00
150	3	0 + j 31.00
200	4	0 + j 45.50
300	5	0 + j 85.00
400	6	0 + j 180 00
500	7	100.0 + j 650.00
600	8	25.0 - j 262.50
700	9	10.0 - j 115.00
800	10	12.5 - j 65.00
900	11	21.5 - j 52.00
1000	12	5.0 - j 3.75

Table XIV

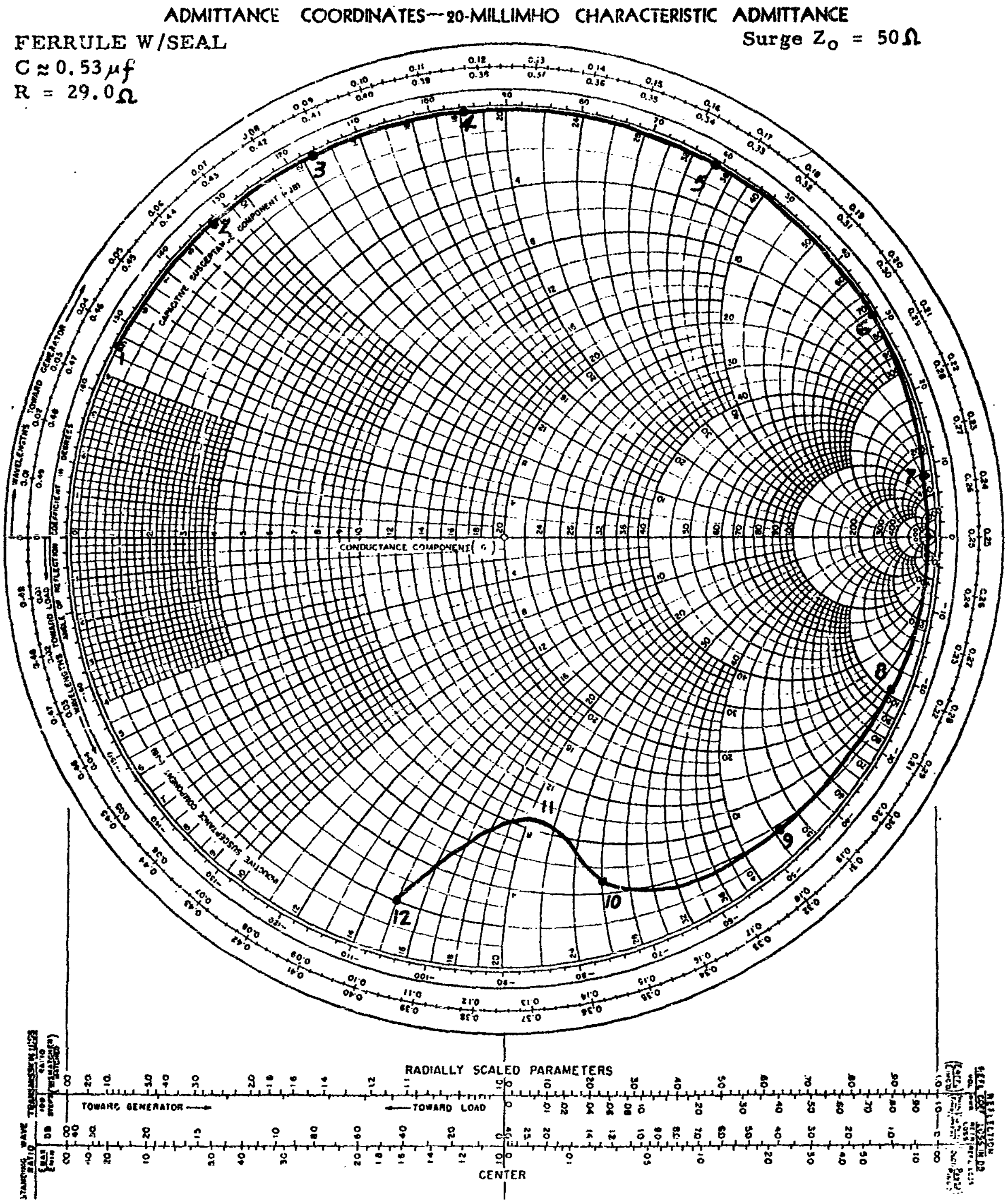


Fig. 28 - Impedance Measurements at Various Frequencies Using Complete Squib Assembly

Impedance Measurements at Various Frequencies Using the American Lava Corporation Ceramic Seal

Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No.	$Z_L (\Omega)$
50	1	0 - j 4000.0
70	2	0 - j 1950.0
100	3	0 - j 1500.0
150	4	0 - j 925.0
200	5	0 - j 750.0
250	6	0 - j 600.0
300	7	0 - j 550.0
350	8	0 - j 435.0
400	9	0 - j 410.0
450	10	0 - j 370.0
500	11	0 - j 310.0
550	12	0 - j 330.0
600	13	0 - j 232.5
650	14	0 - j 210.0
700	15	0 - j 222.5
750	16	0 - j 154.5
800	17	0 - j 111.0
850	18	0 - j 129.0
900	19	0 - j 122.5
950	20	0 - j 108.0
1000	21	0 - j 105.0
1050	22	0 - j 97.0
1100	23	0 - j 93.5
1150	24	0 - j 86.5
1200	25	0 - j 82.0
1250	26	0 - j 79.0
1300	27	0 - j 73.5
1350	28	0 - j 63.0
1400	29	0 - j 57.0
1450	30	0 - j 53.5
1500	31	0 - j 32.0

Table XV

IMPEDANCE OR ADMITTANCE COORDINATES

Surge Z_o = Ω

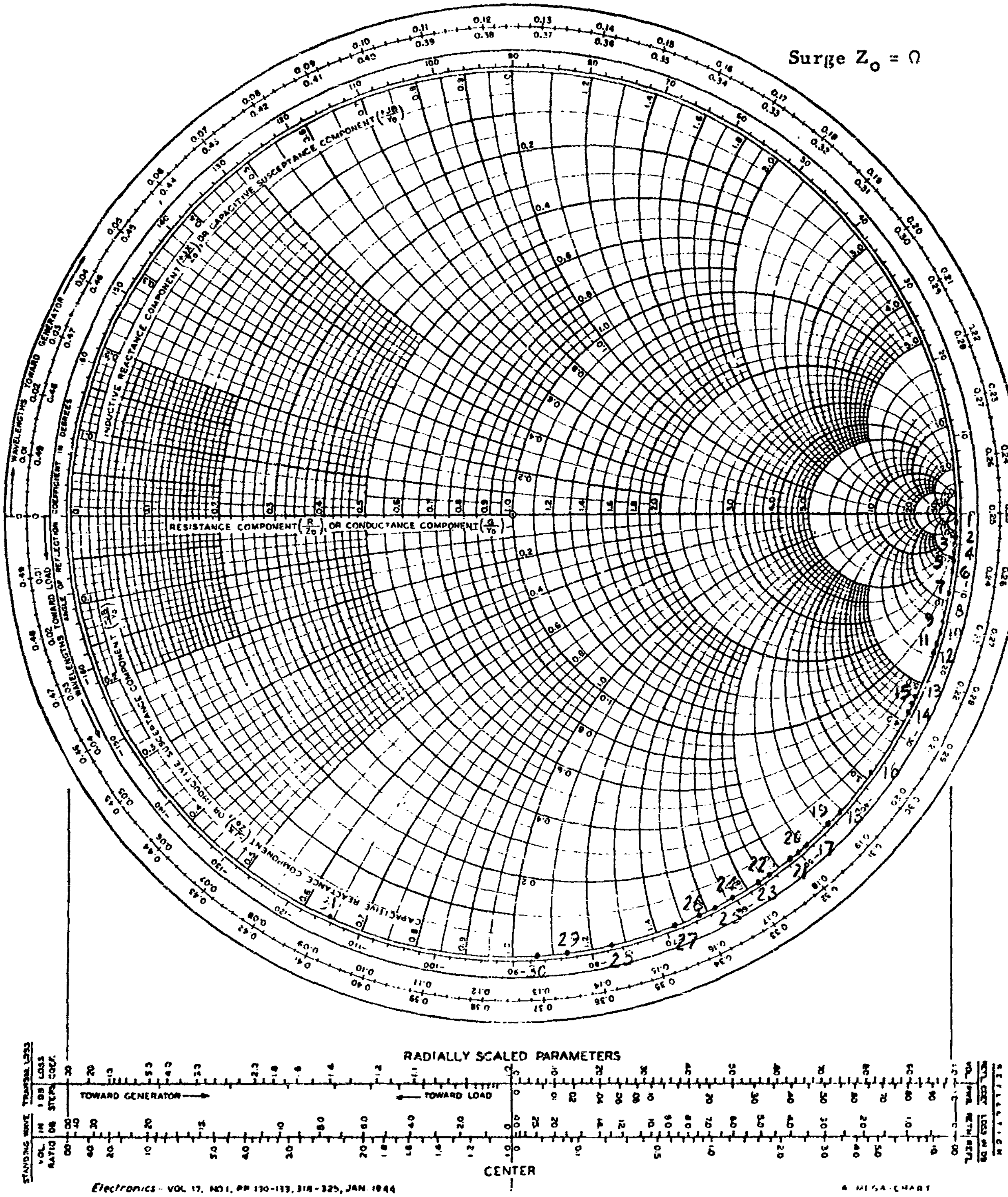


Fig. 29 - Impedance Measurements at Various Frequencies Using American Lava Corporation Ceramic Seal

Impedance Measurements at Various Frequencies Using the Carborundum Company Ceramic Seal

Seal #2 Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No.	Z_L (Ω)
50	1	0 - j 2000.0
70	2	0 - j 1450.0
100	3	0 - j 2750.0
150	4	0 - j 2250.0
200	5	0 - j 690.0
250	6	0 - j 500.0
300	7	0 - j 395.0
350	8	0 - j 315.0
400	9	0 - j 295.0
450	10	0 - j 245.0
500	11	0 - j 245.0
550	12	0 - j 205.0
600	13	0 - j 185.0
650	14	0 - j 151.0
700	15	0 - j 135.0
750	16	0 - j 135.0
800	17	0 - j 120.0
850	18	0 - j 115.0
900	19	0 - j 91.5
950	20	0 - j 101.5
1000	21	0 - j 107.5
1050	22	0 - j 87.0
1100	23	0 - j 83.5
1150	24	0 - j 78.0
1200	25	0 - j 72.0
1250	26	0 - j 62.0
1300	27	0 - j 58.0
1350	28	0 - j 48.5
1400	29	0 - j 43.5
1450	30	0 - j 36.5
1500	31	0 - j 30.0

Table XVI

IMPEDANCE OR ADMITTANCE COORDINATES Surge Z_o = 50Ω

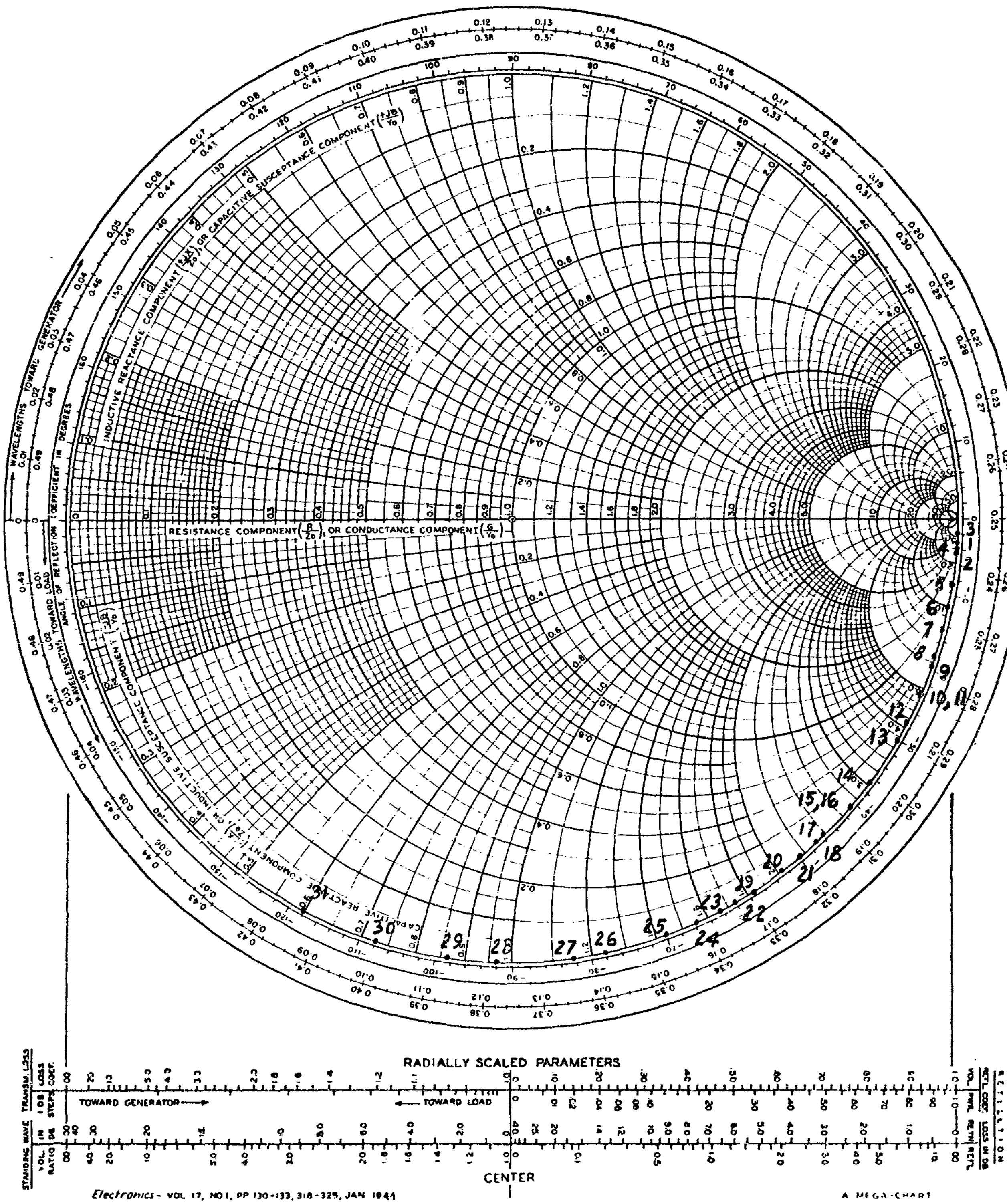


Fig. 30 - Impedance Measurements at Various Frequencies Using the Carborundum Company Ceramic Seal

A-C Characteristics of Six (6) American Lava Corporation Ceramic Seals*

Sample No.	Capacitance ($\mu\mu f$)	Conductance (μ mhos)
1	0.6266	100,000
2	0.6243	"
3	0.6244	"
4	0.6044	"
5	0.6251	"
6	0.6104	"

* Measurements made with Boonton Electrics Corporation Capacitance Bridge Model 75A-58; Test Frequency - 1 MC.

Table XVII

A-C Characteristics of Five (5) Carborundum Company Ceramic Seals*

Sample No.	Capacitance (μμf)	Conductance (μmhos)
1	0.8505	26,000
2	0.8639	15,000
3	0.8501	21,000
4	0.8377	10,000
5	0.8745	11,000

*Measurements made with Boonton Electrics Corporation Capacitance Bridge Model 75A-58; Test Frequency - 1 MC.

Table XVIII

Impedance Measurements at Various Frequencies Using a Representative Sample of the Erie Resistor Corporation Production Model Cylindrical Titanate Capacitance Assembly (Cluster of three (3) units) with Ceramic Mount and One Turn of Bridge Wire.

$C \approx .5\ \mu f$
$R = 13\ \Omega$

Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No.	Z_L (Ω)
250	1	0 + j 34.0
300	2	0 + j 39.5
350	3	0.5 + j 49.5
400	4	0 + j 52.0
450	5	0 + j 66.5
500	6	0 + j 72.5
550	7	0 + j 95.0
600	8	0 + j 111.5
650	9	0 + j 107.5
700	10	0 + j 155.0
750	11	0 + j 175.0
800	12	0 + j 225.0
850	13	70.0 + j 305.0
900	14	450.0 + j 650.0
950	15	600.0 + j 325.0
1000	16	0 - j 2450.0

Table XIX

C ≈ .5μf
R = 13Ω (1 Turn)

IMPEDANCE OR ADMITTANCE COORDINATES Surge Z_0 = 50Ω

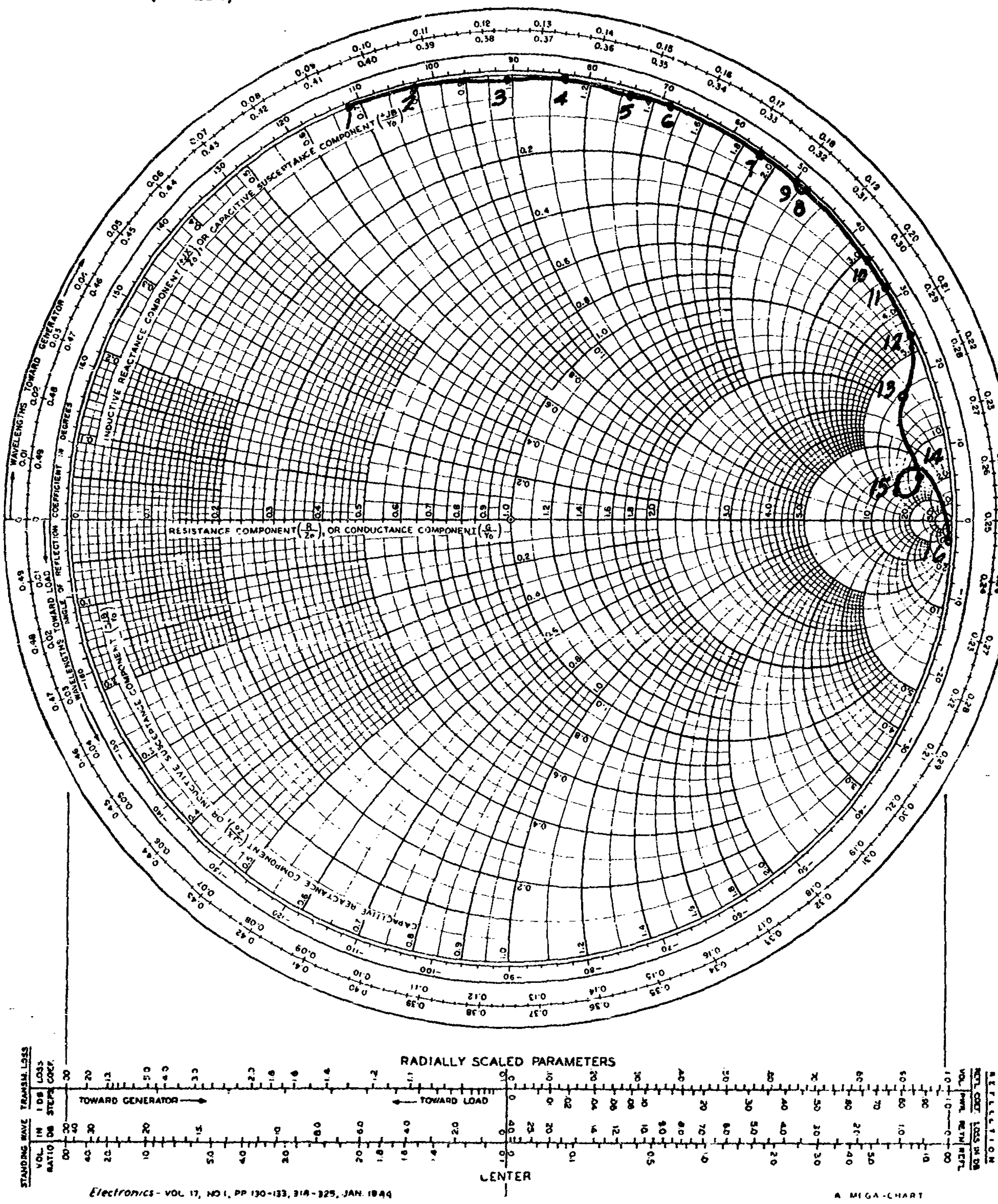


Fig. 31 - Impedance Measurements at Various Frequencies Using a Representative Sample of Erie Resistor Corporation Production Model Capacitance Assembly

Impedance Measurements at Various Frequencies Using Erie Resistor Corporation Production Model Cylindrical Titanate Capacitance Assembly (Cluster of three (3) units), with Teflon Insulated Wire Externally Connected to Assembly, Ceramic Mount, Bridge Wire (1 Turn), without Hermetic Seal.

$C = 0.454\ \mu f$
$R = 21.5\ \Omega$

Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No	Z_L (Ω)
50	1	0 + j 10.5
70	2	0 + j 15.5
100	3	0 + j 20.25
150	4	0 + j 28.5
200	5	1.0 + j 40.0
250	6	0 + j 52.5
300	7	0 + j 64.5
350	8	0 + j 76.5
400	9	0 + j 95.0
450	10	0 + j 107.5
500	11	0 + j 142.5
550	12	0 + j 147.5
600	13	0 + j 195.0
650	14	0 + j 195.0
700	15	0 + j 215.0
750	16	0 + j 250.0
800	17	0 + j 275.0
850	18	0 + j 690.0
900	19	0 + j 800.0
950	20	0 + j 4000.0
1000	21	0 - j 850.0

Table XX

C = 0.454μf
R = 21.5Ω (1 Turn)

Surge Z_o = 50Ω

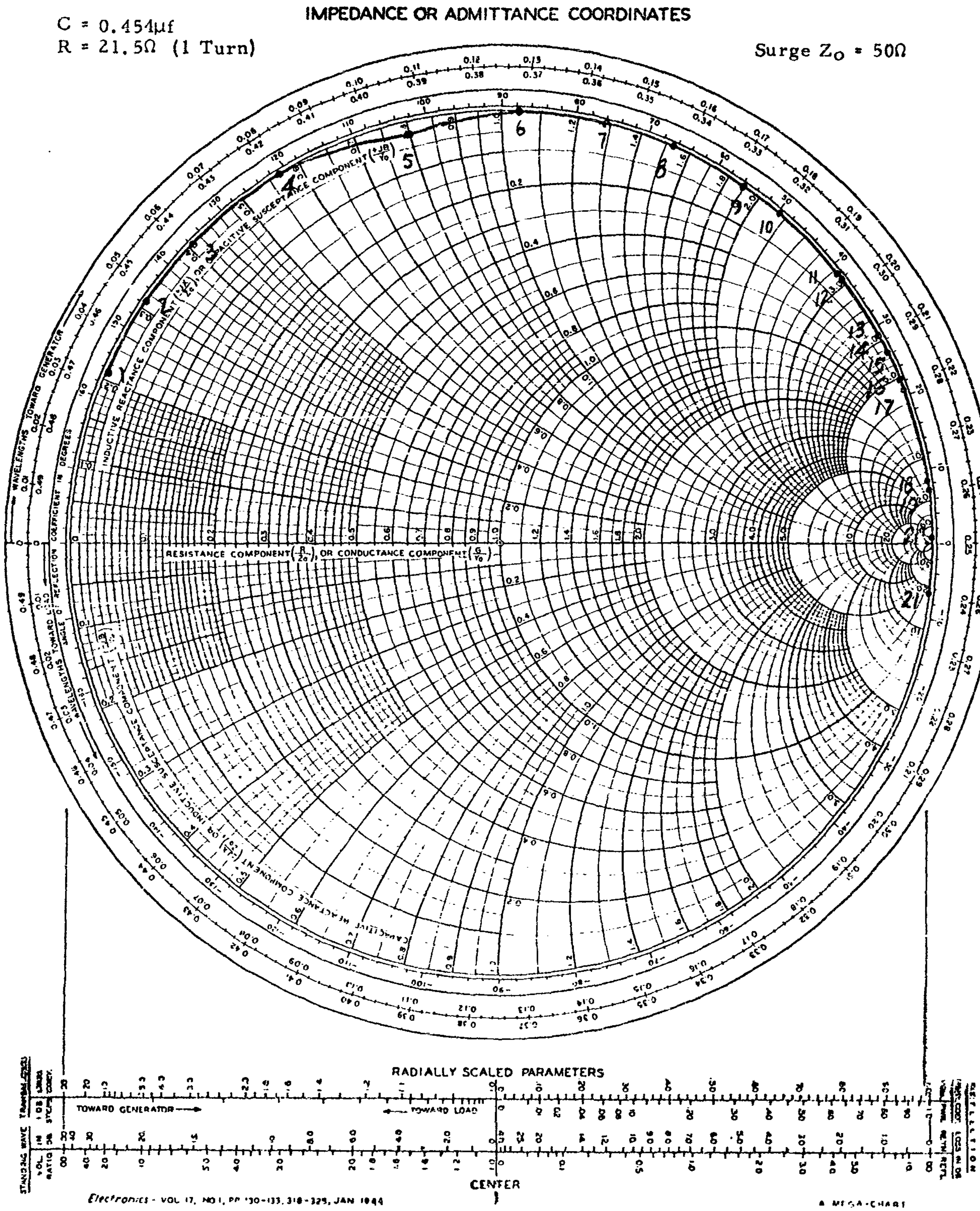


Fig. 32 - Impedance Measurements at Various Frequencies Using Erie Resistor Corporation Capacitance Assembly

Impedance Measurements at Various Frequencies Using Erie Resistor Corporation Production Model Cylindrical Titanate Capacitance Assembly (Cluster of three (3) units), with Teflon Insulated Wire Externally Connected to Assembly, Ceramic Mount and Bridge Wire (2 Turns), without Hermetic Seal.

$C = 0.454\ \mu f$ Surge $Z_o = 50\ \Omega$
$R = 34.0\ \Omega$

Frequency (mc)	Point No.	$Z_L(\Omega)$
50	1	1.0 + j 11.0
70	2	0 + j 16.5
100	3	0 + j 23.0
150	4	0 + j 31.0
200	5	0 + j 43.0
250	6	0 + j 55.5
300	7	1.0 + j 65.5
350	8	4.0 + j 77.5
400	9	0 + j 76.5
450	10	0 + j 111.0
500	11	0 + j 120.5
550	12	0 + j 175.0
600	13	0 + j 146.0
650	14	0 + j 197.5
700	15	0 + j 215.0
750	16	0 + j 275.0
800	17	0 + j 375.0
850	18	0 + j 700.0
900	19	0 + j 1000.0
950	20	0 + j 3500.0
1000	21	0 - j 900.0

Table XXI

C = 0.454 μf
R = 34.0Ω (2 Turns)

Surge Z_o = 50Ω

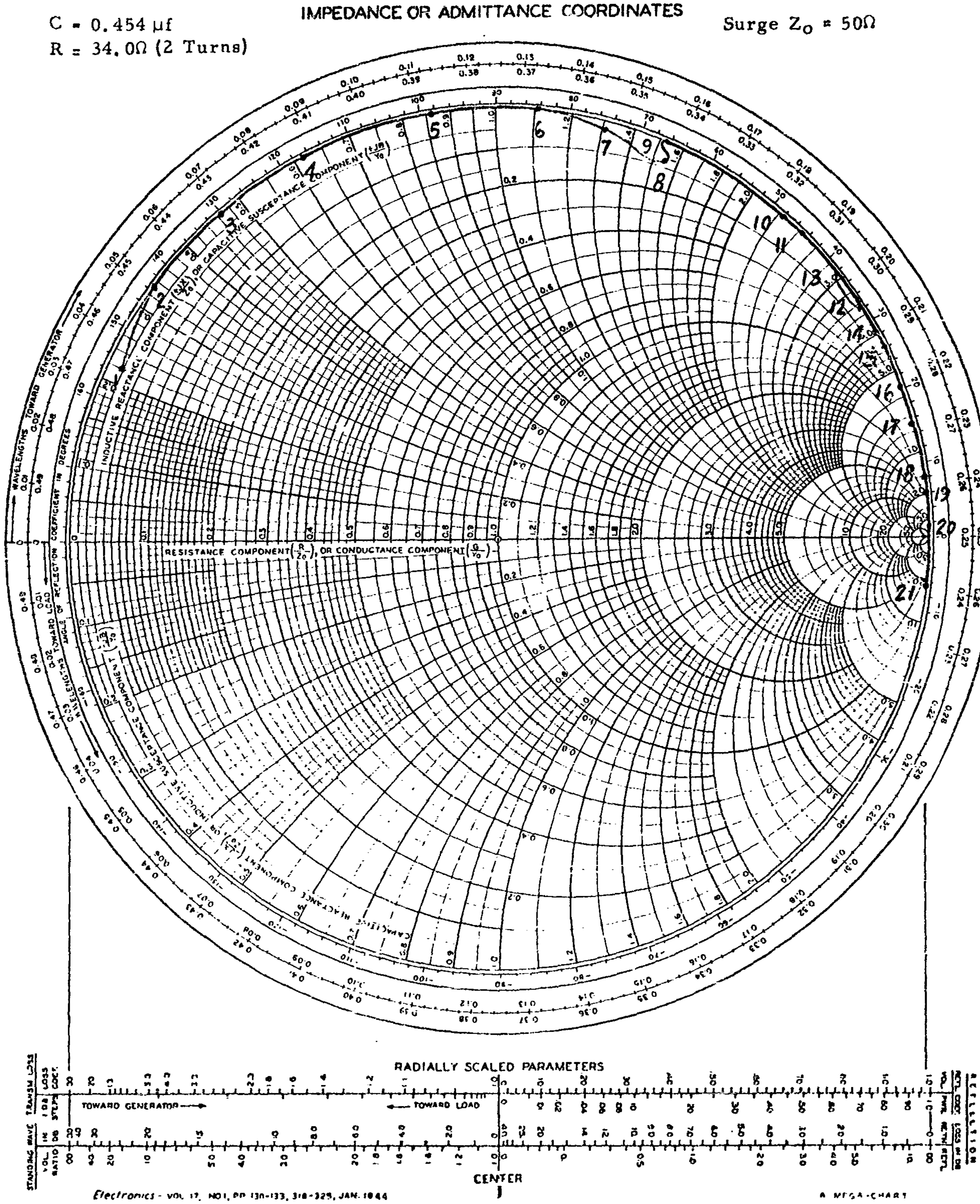


Fig. 33 - Impedance Measurements at Various Frequencies Using Erie Resistor Corporation Capacitance Assembly

Impedance Measurements at Various Frequencies Using Erie Resistor Corporation Production Model Cylindrical Titanate Capacitance Assembly (Cluster of three (3) units), with Teflon Insulated Wire Externally Connected to Assembly Ceramic Mount, Bridge Wire (1 Turn), and Hermetic Seal.

$C \approx 0.5\ \mu f$
$R = 19.2\ \Omega$

Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No.	Z_L (Ω)
50	1	0.50 + j 9.25
70	2	0.75 + j 14.00
100	3	0 + j 16.95
150	4	0 + j 27.00
200	5	1.5 + j 40.50
300	6	0.5 + j 65.00
350	7	0.5 + j 78.00
400	8	5.0 + j 90.00
450	9	6.0 + j 115.00
500	10	0 + j 170.50
550	11	0 + j 280.00
600	12	0 + j 250.00
650	13	0 + j 525.00
700	14	0 + j 2000.00
750	15	50.0 - j 900.00
800	16	0 - j 220.00
850	17	7.5 - j 160.00
900	18	9.0 - j 112.50
950	19	5.0 - j 77.00
1000	20	2.5 - j 55.00

Table XXII

C ≈ 0.5μf
R = 19.2Ω (1 Turn)

IMPEDANCE OR ADMITTANCE COORDINATES

Surge Z_0 = 50Ω

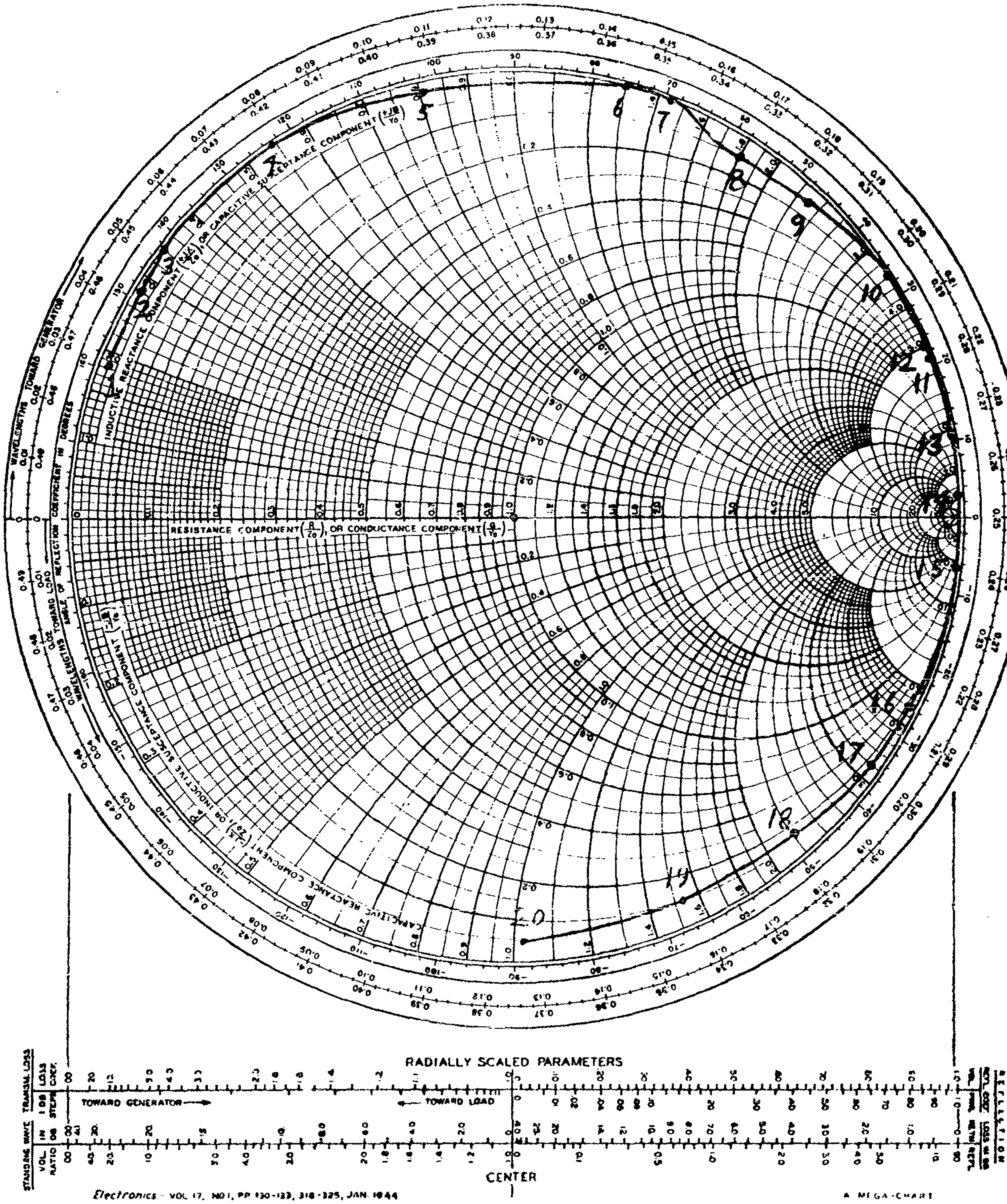


Fig. 34 - Impedance Measurements at Various Frequencies Using Erie Resistor Corporation Capacitance Assembly

Impedance Measurements at Various Frequencies Using Erie Resistor Corporation Production Model Cylindrical Titanate Capacitance Assembly (Cluster of three (3) Units), with Teflon Insulated Wire Externally Connected to Assembly, Ceramic Mount, Bridge Wire (2 turns), and Hermetic Seal.

$C \approx 0.5\ \mu f$ Surge $Z_o = 50\ \Omega$

$R = 34.0\ \Omega$

Frequency (mc)	Point No.	Z_L (Ω)
50	1	6.75 + j 10.45
70	2	5.0 + j 16.0
100	3	2.5 + j 22.25
150	4	2.0 + j 34.0
200	5	2.7 + j 47.0
250	6	5.0 + j 61.5
300	7	0 + j 99.5
350	8	5.0 + j 91.0
400	9	0 + j 118.0
450	10	9.5 + j 140.0
500	11	0 + j 240.0
550	12	0 + j 220.0
600	13	0 + j 310.0
650	14	0 + j 475.0
700	15	0 + j 360.0
750	16	0 + j 2500.0
800	17	0 - j 2250.0
850	18	0 - j 380.0
900	19	10.0 - j 220.0
950	20	5.0 - j 145.0
1000	21	7.5 - j 91.0

Table XXIII

C ≈ 0.5 μf
R = 34.0Ω (2 Turns)

IMPEDANCE OR ADMITTANCE COORDINATES

Surge Z_o = 50Ω

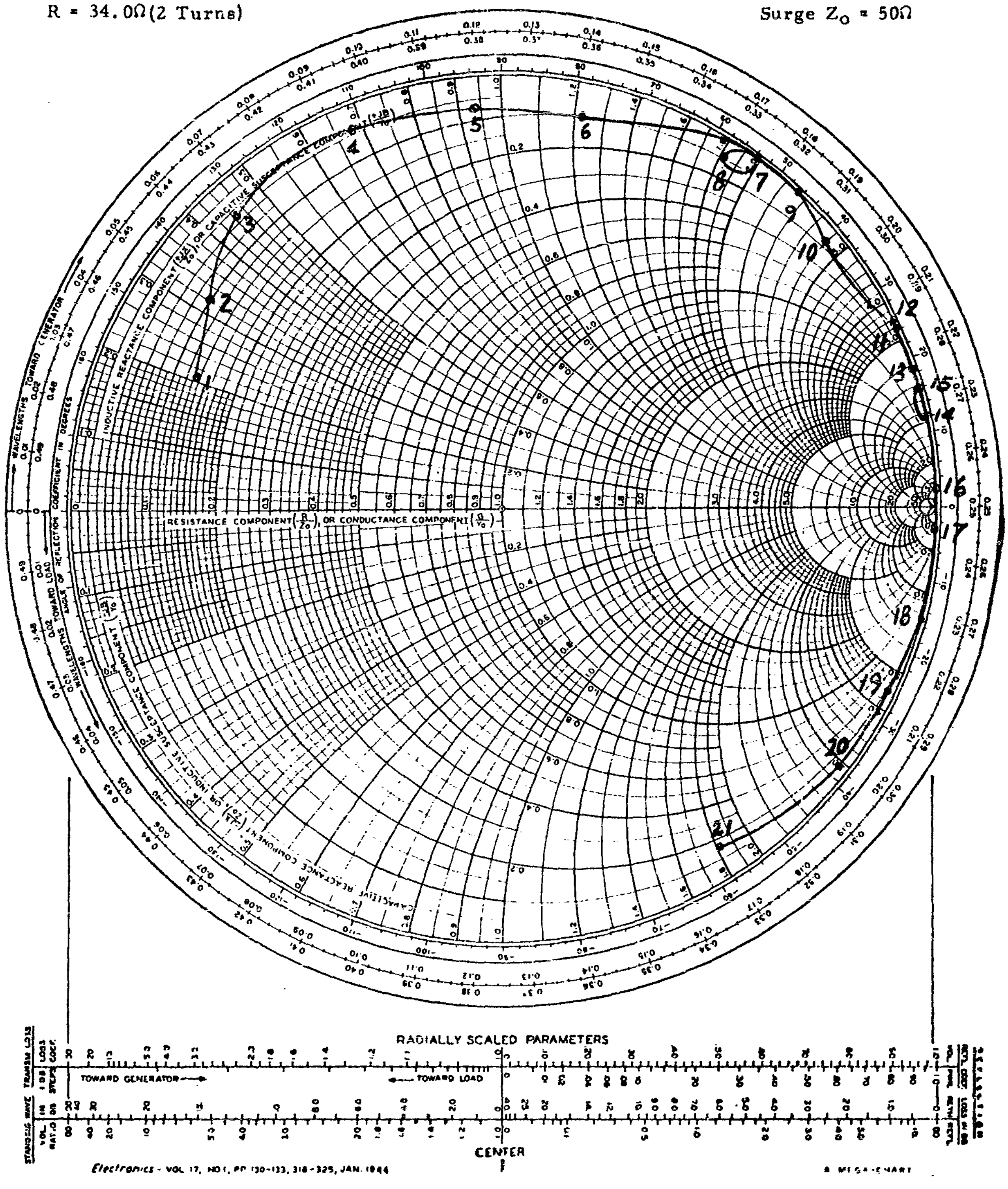


Fig. 35 - Impedance Measurements at Various Frequencies Using Erie Resistor Corporation Capacitance Assembly

Impedance Measurements at Various Frequencies Using a Complete Squib Assembly w/modified Erie Resistor Corporation Production Model Cylindrical Titanate Capacitance Assembly (cluster of three (3) units), One (1) Turn of Bridge Wire, fifteen (15) grains of A-5 Black Powder, Lead Styphnate Bead Mix, Insulating Vinyl Tubing, and Hermetic Seal

$C \approx 0.5\ \mu f$
$R = 15\ \Omega$

Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No.	$Z_L (\Omega)$
50	1	0 + j 10.50
70	2	0 + j 13.50
100	3	0 + j 18.75
150	4	1.5 + j 27.50
200	5	6.0 + j 34.0
250	6	3.5 + j 44.5
300	7	2.5 + j 62.0
350	8	6.0 + j 77.5
400	9	10.0 + j 94.5
450	10	10.0 + j 105.0
500	11	7.5 + j 116.0
550	12	15.5 + j 107.5
600	13	9.0 + j 157.0
650	14	0 + j 250.0
700	15	0 + j 450.0
750	16	0 - j 700.0
800	17	120.0 - j 505.0
850	18	100.0 - j 350.0
900	19	230.0 - j 29.5
950	20	85.0 - j 215.0
1000	21	110.0 - j 205.0

Table XXIV

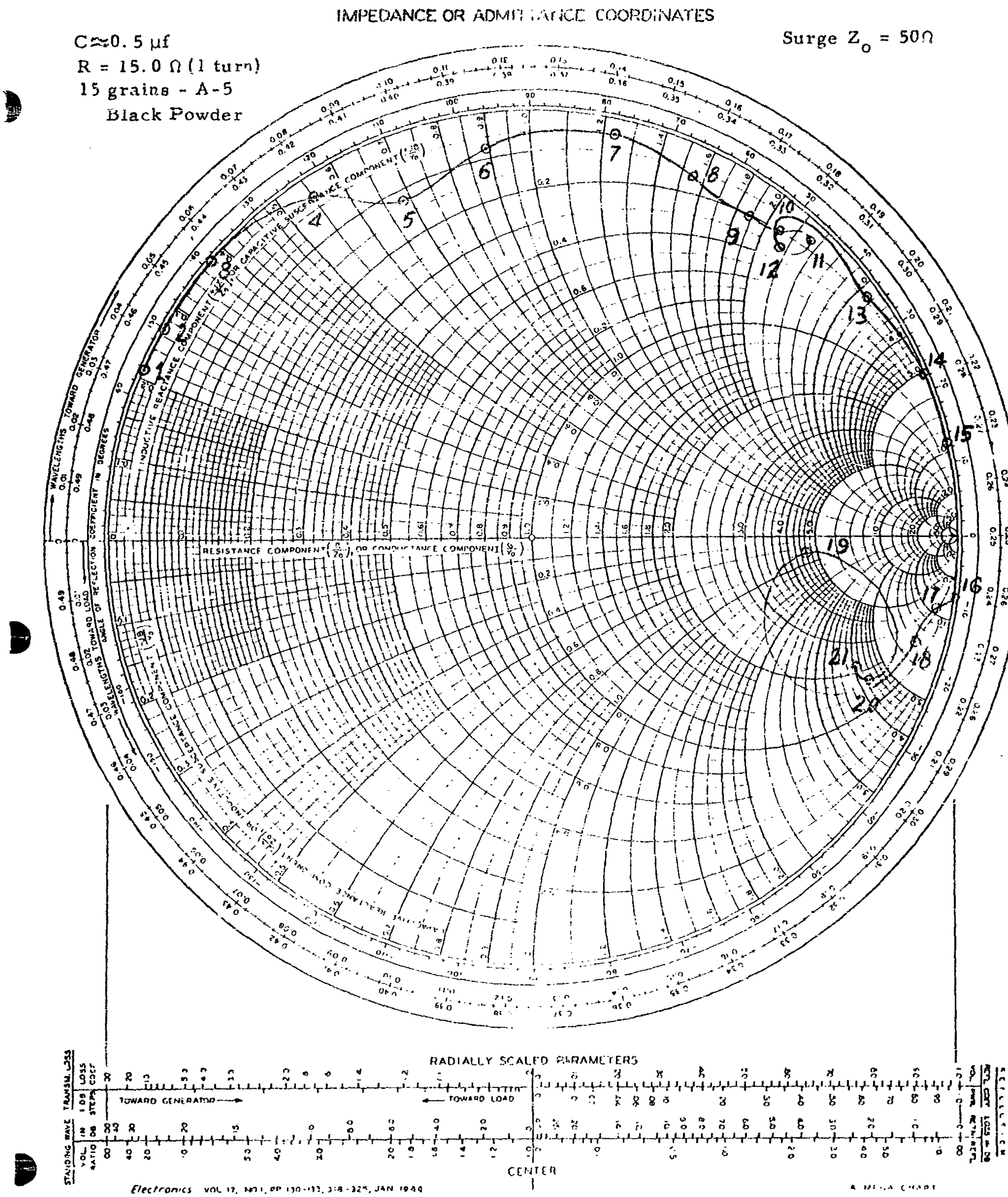


Fig. 36 - Impedance Measurements at Various Frequencies Using Complete Squib Assembly w/Erie Resistor Corporation Capacitance Assembly

Impedance Measurements at Various Frequencies Using a Complete Squib Assembly w/Modified Erie Resistor Corporation Production Model Cylindrical Titanate Capacitance Assembly (cluster of three (3) units), Two (2) Turns of Bridge Wire, fifteen (15) grains of A-5 Black Powder, Lead Styphnate Bead Mix, Insulating Vinyl Tubing, and Hermetic Seal.

$C \approx 0.5\ \mu f$
$R = 32.0\ \Omega$

Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No.	Z_L (Ω)
50	1	0 + j 13.5
70	2	0 + j 16.0
100	3	0 + j 22.0
150	4	0 + j 31.5
200	5	8.5 + j 33.5
250	6	11.5 + j 54.5
300	7	6.5 + j 71.0
350	8	9.5 + j 91.0
400	9	15.0 + j 107.0
450	10	25.0 + j 130.0
500	11	42.5 + j 79.5
550	12	39.5 + j 105.0
600	13	11.0 + j 210.0
650	14	0 + j 45.0
700	15	0 - j 3000.0
750	16	5.0 - j 300.0
800	17	20.0 - j 180.0
850	18	65.0 - j 220.0
900	19	62.5 - j 122.0
950	20	64.5 - j 69.0
1000	21	69.5 - j 91.0

Table XXV

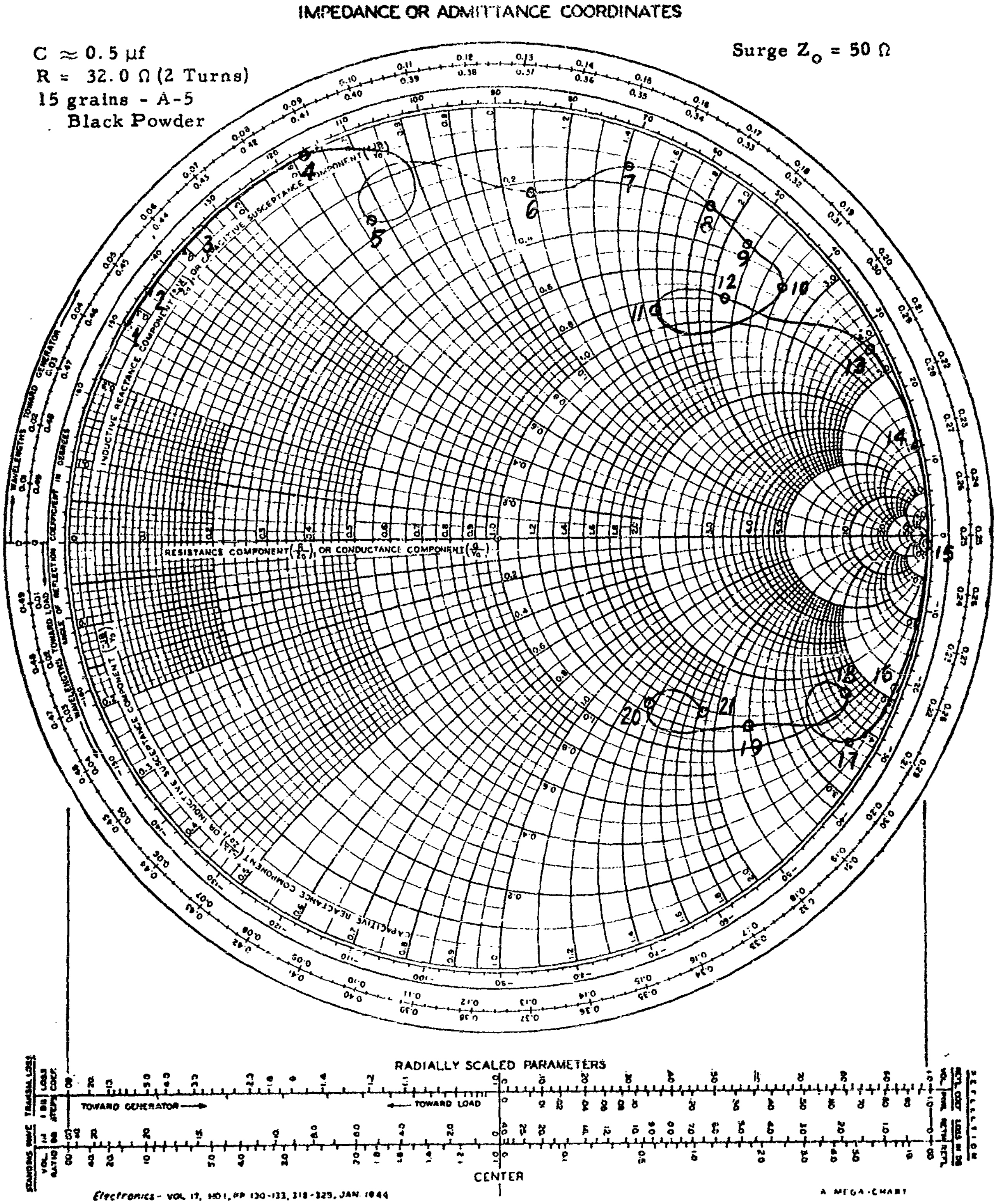


Fig. 37 - Impedance Measurements at Various Frequencies Using Complete Squib Assembly w/Erie Resistor Corporation Capacitance Assembly

Impedance Measurements at Various Frequencies Using a Complete Squib Assembly w/modified Erie Resistor Corporation Production Model Cylindrical Titanate Capacitance Assembly (cluster of three (3) units), One (1) Turn of Bridge Wire, ten (10) grains of A-5 Black Powder, Lead Styphnate Bead Mix, Insulating Vinyl Tubing and Hermetic Seal.

$C \approx 0.5\ \mu f$
$R = 15.0\ \Omega$

Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No.	Z_L (Ω)
50	1	0 + j 10.5
70	2	0 + j 14.0
100	3	0 + j 17.5
150	4	4.0 + j 23.5
200	5	4.0 + j 32.5
250	6	4.5 + j 40.0
300	7	5.0 + j 49.0
350	8	6.0 + j 59.5
400	9	7.5 + j 71.0
450	10	9.0 + j 85.0
500	11	7.5 + j 101.5
550	12	2.0 + j 130.0
600	13	9.5 + j 190.0
650	14	10.0 + j 220.0
700	15	10.0 + j 450.0
750	16	375.0 + j 2500.0
800	17	2.5 - j 44.0
850	18	3.0 - j 18.0
900	19	4.5 + j 10.0
950	20	6.0 + j 27.5
1000	21	8.0 + j 46.5

Table XXVI

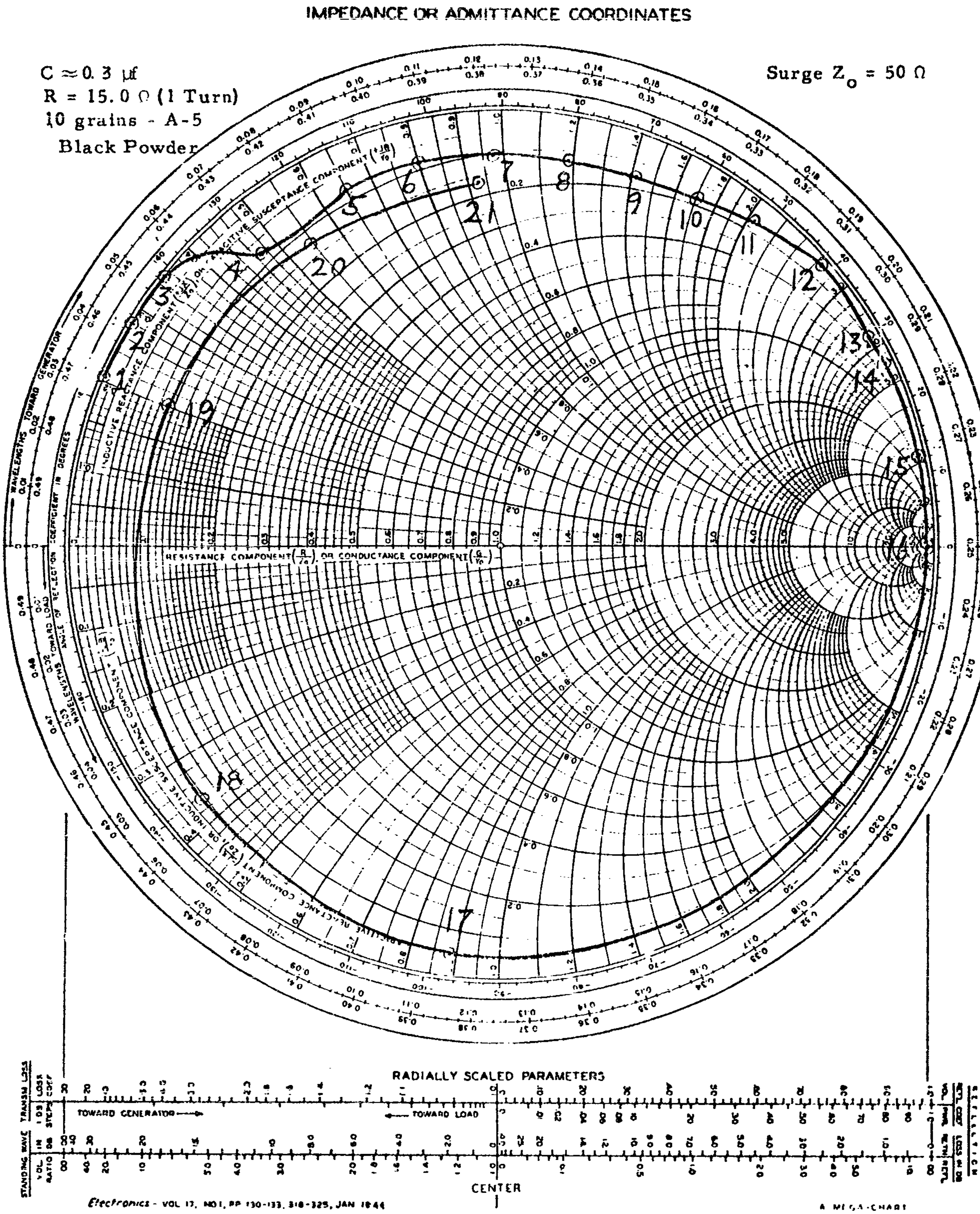


Fig. 38 - Impedance Measurements at Various Frequencies Using Complete Squib Assembly w/Erie Resistor Corporation Capacitance Unit

Impedance Measurements at Various Frequencies Using a Complete Squib Assembly w/modified Erie Resistor Corporation Production Model Cylindrical Titanate Capacitance Assembly (cluster of three (3) units), Two (2) Turns of Bridge Wire, ten (10) grains of A-5 Black Powder, Lead Styphnate Bead Mix, Insulating Vinyl Tubing and Hermetic Seal.

$C \approx 0.5\ \mu f$
$R = 27.0\ \Omega$

Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No.	Z_L (Ω)
50	1	0 + j 3.5
70	2	0 + j 13.5
100	3	0 + j 17.0
150	4	2.0 + j 24.5
200	5	1.5 + j 34.5
250	6	0 + j 47.0
300	7	0 + j 59.5
350	8	0 + j 71.0
400	9	2.0 + j 87.5
450	10	5.0 + j 112.5
500	11	0 + j 155.0
550	12	5.0 + j 220.0
600	13	15.0 + j 375.0
650	14	0 + j 2500.0
700	15	20.0 - j 420.0
750	16	5.0 - j 132.5
800	17	1.0 - j 72.0
850	18	0.5 - j 37.0
900	19	1.0 - j 7.5
950	20	7.5 + j 19.0
1000	21	2.0 + j 44.5

Table XXVII

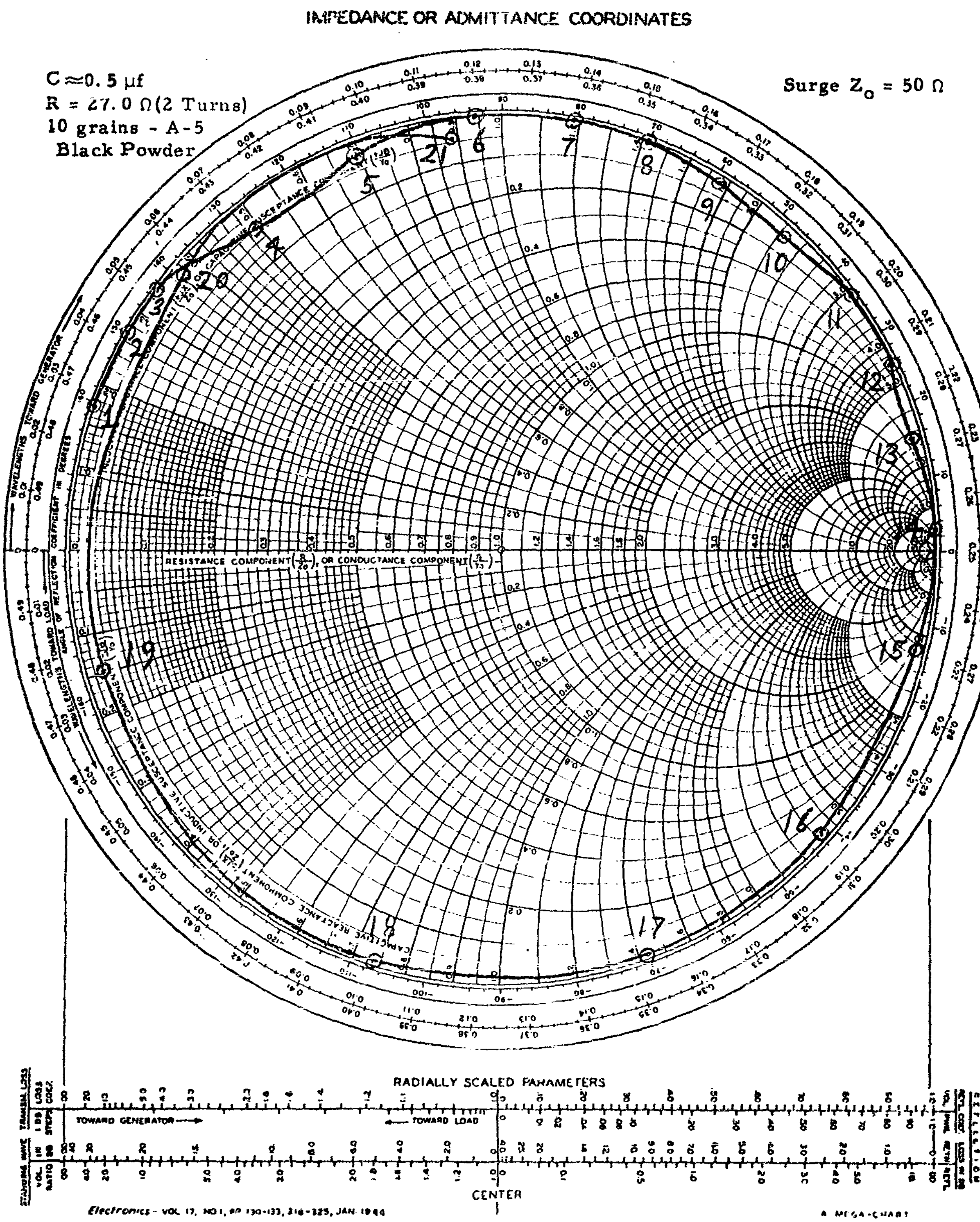


Fig. 39 - Impedance Measurements at Various Frequencies Using Complete Squib Assembly w/Erie Resistor Corporation Capacitance Assembly

Impedance Measurements at Various Frequencies Using a Complete Squib Assembly w/modified Erie Resistor Corporation Production Model Cylindrical Titanate Capacitance Assembly (cluster of three (3) units), One (1) Turn of Bridge Wire, five (5) grains of A-5 Black Powder, Lead Styphnate Bead Mix, Insulating Vinyl Tubing, and Hermetic Seal.

$C \approx 0.5\ \mu f$
$R = 15.8\ \Omega$

Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No.	Z_L (Ω)
50	1	0 + j 10.0
70	2	0 + j 14.5
100	3	0 + j 17.5
150	4	2.0 + j 25.5
200	5	4.5 + j 36.5
250	6	1.5 + j 48.0
300	7	0.5 + j 60.5
350	8	0.5 + j 74.0
400	9	0.5 + j 95.0
450	10	0 + j 120.0
500	11	0 + j 159.5
550	12	0 + j 232.5
600	13	10.0 + j 500.0
650	14	2500.0 + j 2500.0
700	15	10.0 - j 350.0
750	16	0 - j 130.0
800	17	0 - j 49.0
850	18	1.0 - j 29.5
900	19	1.0 - j 2.0
950	20	4.5 + j 25.5
1000	21	4.5 + j 46.0

Table XXVIII

IMPEDANCE OR ADMITTANCE COORDINATES

C ≈ 0.5 μf
R = 15.8 Ω (1 Turn)
5 grains - A-5
Black Powder

Surge Z_0 = 50 Ω

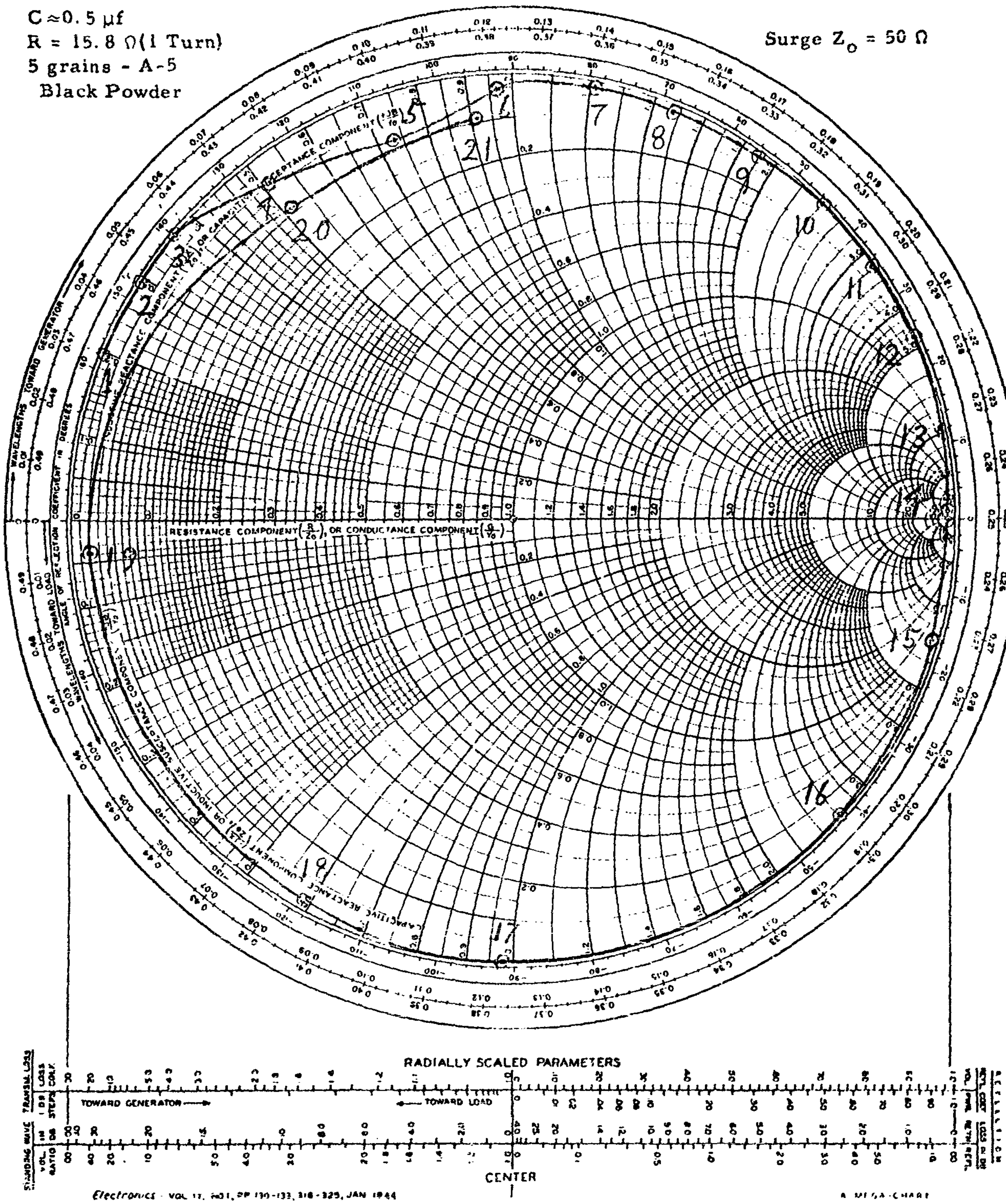


Fig. 40 - Impedance Measurements at Various Frequencies Using Complete Squib Assembly w/Erie Resistor Corporation Capacitance Assembly

Impedance Measurements at Various Frequencies Using a Complete Squib Assembly w/modified Erie Resistor Corporation Production Model Cylindrical Titanate Capacitance Assembly (cluster of three (3) units), Two (2) Turns of Bridge Wire, five (5) grains of A-5 Black Powder, Lead Styphnate Bead Mix, Insulating Vinyl Tubing and Hermetic Seal.

$C \approx 0.5\ \mu f$
$R = 30.0\ \Omega$

Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No.	Z_L (Ω)
50	1	0 + j 9.5
70	2	0 + j 14.0
100	3	0 + j 18.0
150	4	1.0 + j 26.5
200	5	3.0 + j 36.0
250	6	1.5 + j 47.5
300	7	6.0 + j 56.5
350	8	5.0 + j 72.5
400	9	6.0 + j 93.5
450	10	2.5 + j 150.0
500	11	7.5 + j 156.0
550	12	0 + j 275.0
600	13	0 + j 500.0
650	14	500.0 + j 2000.0
700	15	40.0 - j 460.0
750	16	5.0 - j 172.5
800	17	0 - j 91.0
850	18	0 - j 51.5
900	19	0.5 - j 18.0
950	20	0 + j 1.0
1000	21	0 + j 25.0

Table XXIX

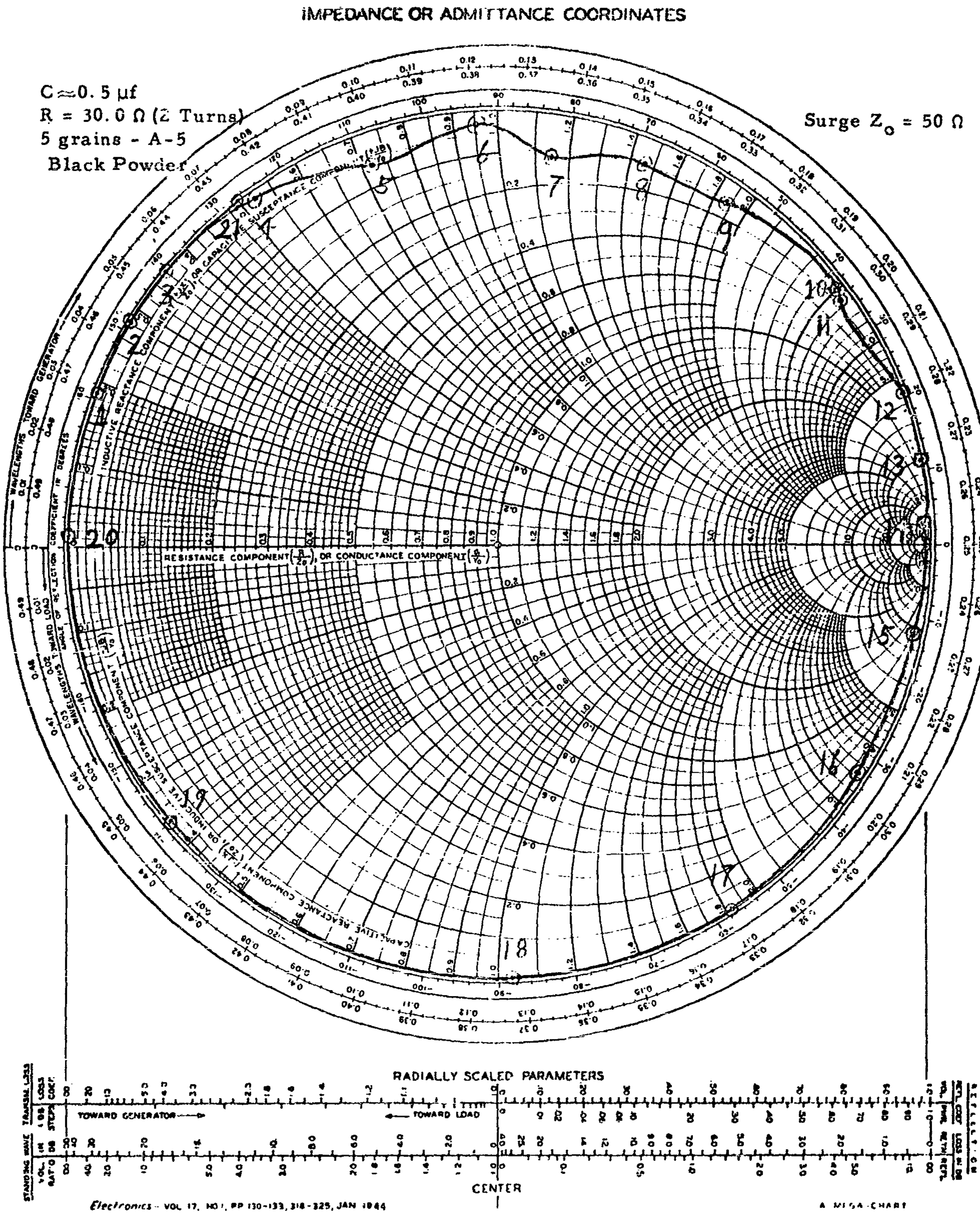


Fig. 41 - Impedance Measurements at Various Frequencies Using Complete Squib Assembly w/Erie Resistor Corporation Capacitance Assembly

Impedance Measurements at Various Frequencies Using American Lava Corporation Production Model Cylindrical Titanate Capacitance Assembly (cluster of three (3) units) and Hermetic Seal.

$C = 0.3\ \mu f$ Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No.	Z_L (Ω)
50	1	0 + j 7.0
70	2	2.0 + j 9.5
100	3	0 + j 12.5
150	4	2.0 + j 15.0
200	5	1.0 + j 23.5
250	6	1.0 + j 31.0
300	7	1.0 + j 36.5
350	8	1.0 + j 45.0
400	9	0.5 + j 51.0
450	10	0.5 + j 60.0
500	11	0 + j 67.5
550	12	0 + j 77.5
600	13	0 + j 94.5
650	14	0 + j 105.0
700	15	0 + j 135.0
750	16	0 + j 155.0
800	17	0 + j 235.0
850	18	0 + j 700.0
900	19	0 + j 2500.0
950	20	0 - j 265.0
1000	21	0 - j 135.0

Table XXX

IMPEDANCE OR ADMITTANCE COORDINATES

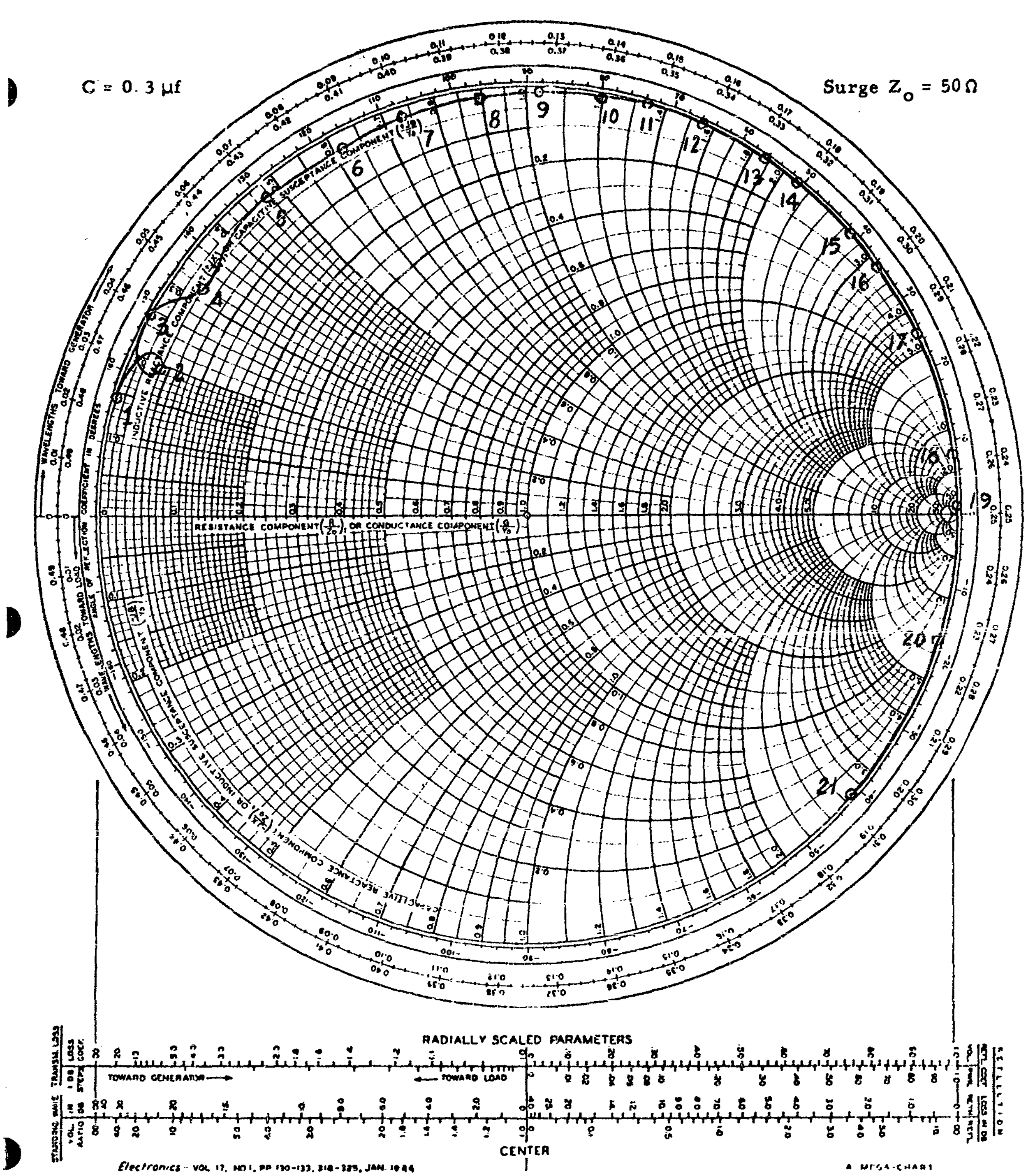


Fig. 42 - Impedance Measurements at Various Frequencies Using American Lava Corporation Capacitance Assembly

Impedance Measurements at Various Frequencies Using An American Lava Corporation Production Model Cylindrical Titanate Capacitance Assembly (cluster of three (3) units), w/One (1) turn of Bridge Wire and Hermetic Seal

$C = 0.3\ \mu f$ Surge $Z_o = 50\ \Omega$

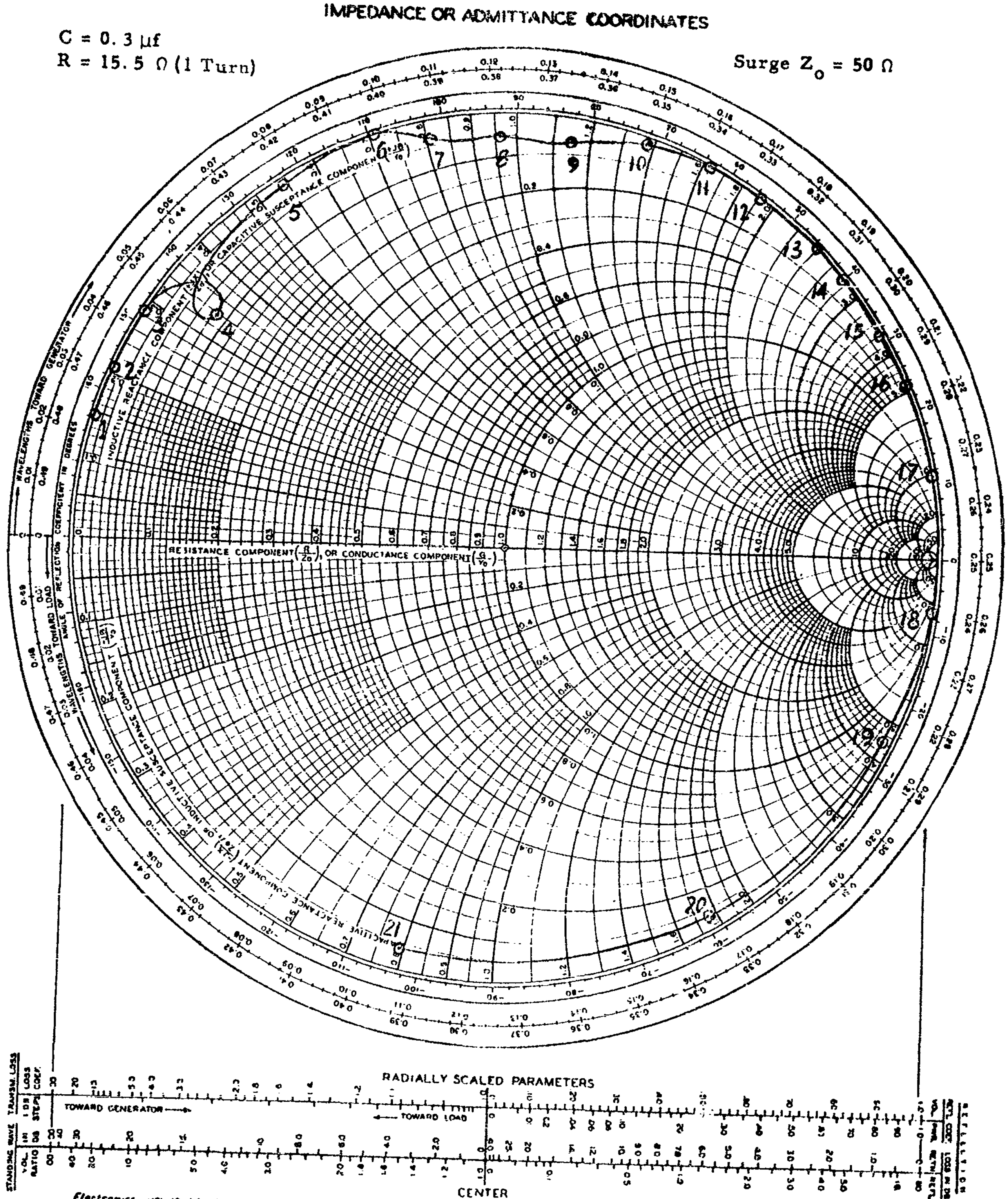
$R = 15.5\ \Omega$

Frequency (mc)	Point No.	Z_L (Ω)
50	1	0 + j 7.0
70	2	0 + j 10.5
100	3	0 + j 14.5
150	4	4.5 + j 17.0
200	5	1.0 + j 27.0
250	6	0 + j 36.0
300	7	1.5 + j 40.5
350	8	2.5 + j 48.0
400	9	4.0 + j 57.5
450	10	1.0 + j 69.5
500	11	0 + j 81.0
550	12	0 + j 96.0
600	13	0 + j 120.0
650	14	0 + j 134.5
700	15	0 + j 180.0
750	16	0 + j 240.0
800	17	0 + j 500.0
850	18	0 - j 800.0
900	19	1.0 - j 220.0
950	20	1.5 - j 88.0
1000	21	2.0 - j 39.5

Table XXXI

C = 0.3 µf
R = 15.5 Ω (1 Turn)

Surge Z_o = 50 Ω



. Fig. 43 - Impedance Measurements at Various Frequencies Using American Lava Corporation Capacitance Assembly

Impedance Measurements at Various Frequencies Using an American Lava Corporation Production Model Cylindrical Titanate Capacitance Assembly (cluster of three (3) units), w/Two Turns of Bridge Wire & Hermetic Seal.

$C = 0.3\ \mu f$
$R = 33.0\ \Omega$

Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No.	Z_L (Ω)
50	1	0 + j 8.0
70	2	0 + j 10.0
100	3	0 + j 18.5
150	4	0 + j 20.5
200	5	1.0 + j 25.5
250	6	0.5 + j 31.0
300	7	0.5 + j 40.0
350	8	1.5 + j 46.0
400	9	0.5 + j 54.5
450	10	0 + j 62.5
500	11	0.5 + j 69.5
550	12	0.5 + j 75.5
600	13	0 + j 92.0
650	14	0 + j 100.5
700	15	0 + j 120.5
750	16	0 + j 145.0
800	17	0 + j 175.0
850	18	0 + j 295.0
900	19	0.5 + j 550.0
950	20	1000.0 - j 2500.0
1000	21	10.0 - j 250.0

Table XXXII

IMPEDANCE OR ADMITTANCE COORDINATES

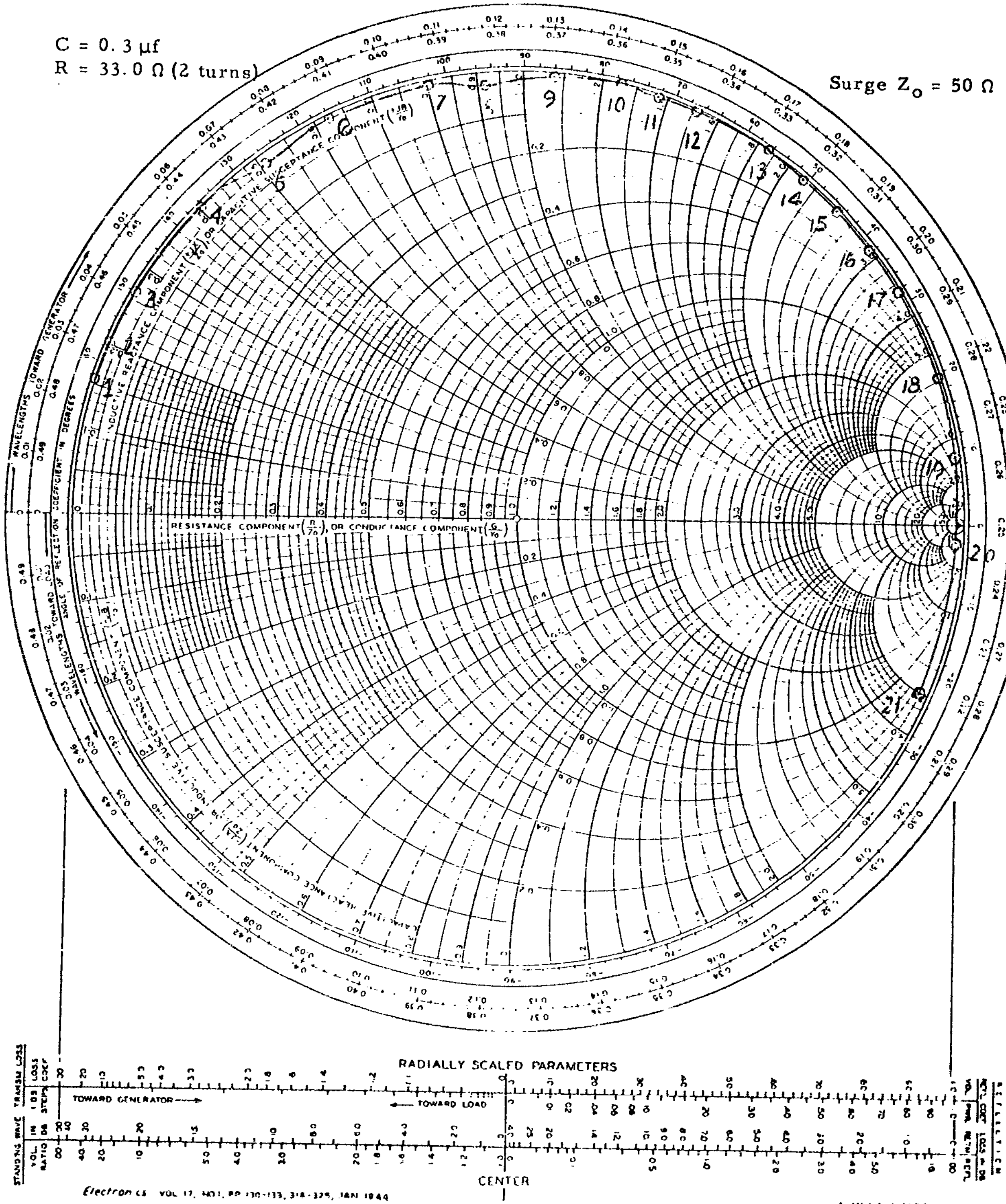


Fig. 44 - Impedance Measurements at Various Frequencies Using American Lava Corporation Capacitance Assembly

Impedance Measurements at Various Frequencies Using a Complete Squib Assembly w/American Lava Corporation Production Model Cylindrical Titanate Capacitance Assembly (cluster of three (3) units) One (1) Turn of Bridge Wire, fifteen (15) grains of A-5 Black Powder, Lead Styphnate Bead Mix, Insulating Vinyl Tubing and Hermetic Seal.

$C = 0.3\ \mu f$
$R = 16.0\ \Omega$

Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No.	Z_L (Ω)
50	1	0 + j 5.5
70	2	3.0 + j 6.0
100	3	2.5 + j 6.5
150	4	0.5 + j 11.0
200	5	0 + j 14.0
250	6	0 + j 19.0
300	7	1.5 + j 21.5
350	8	2.0 + j 26.0
400	9	3.0 + j 29.5
450	10	2.0 + j 34.0
500	11	1.5 + j 35.5
550	12	0 + j 47.0
600	13	1.0 + j 50.5
650	14	0.5 + j 62.5
700	15	0 + j 87.5
750	16	0 + j 82.5
800	17	0 + j 120.0
850	18	0 + j 225.0
900	19	0 - j 1250.0
950	20	2.5 - j 86.5
1000	21	1.0 - j 16.0

Table XXXIII

IMPEDANCE OR ADMITTANCE COORDINATES

C = 0.3 μf
R = 16.0 Ω (1 Turn)
15 grains - A-5
Black Powder

Surge Z_o = 50 Ω

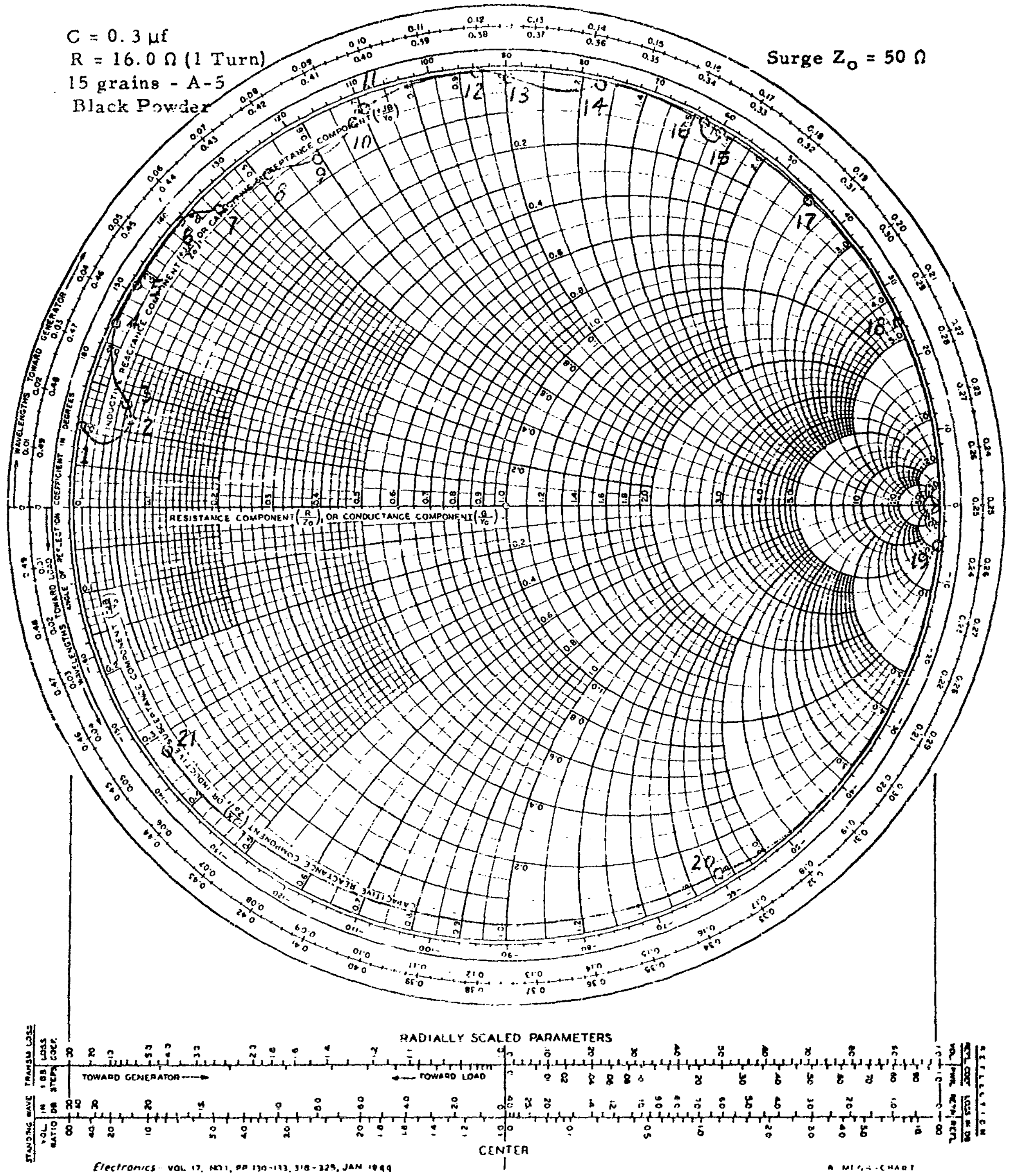


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Fig. 45 - Impedance Measurements at Various Frequencies Using a Complete Squib Assembly w/American Lava Corporation Capacitance Assembly

Impedance Measurements at Various Frequencies Using a Complete Squib Assembly w/American Lava Corporation Production Model Cylindrical Titanate Capacitance Assembly (cluster of three (3) units), Two (2) Turns of Bridge Wire, fifteen (15) grains of A-5 Black Powder, Lead Styphnate Mix, Insulating Vinyl Tubing, and Hermetic Seal.

$C = 0.3\ \mu f$
$R = 33.0\ \Omega$

Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No.	Z_L (Ω)
50	1	0 + j 6.5
70	2	2.0 + j 9.5
100	3	0 + j 11.8
150	4	1.9 + j 16.5
200	5	2.8 + j 22.5
250	6	1.0 + j 29.0
300	7	1.0 + j 35.5
350	8	1.5 + j 42.0
400	9	2.5 + j 48.0
450	10	2.5 + j 56.5
500	11	2.0 + j 65.5
550	12	0.5 + j 81.5
600	13	0.5 + j 93.5
650	14	0.5 + j 110.0
700	15	3.0 + j 151.5
750	16	7.5 + j 225.0
800	17	0.0 - j 2000.0
850	18	1.5 - j 106.5
900	19	0.5 - j 34.5
950	20	1.5 + j 23.0
1000	21	0 + j 44.0

Table XXXIV

C = 0.3 µf
R = 33.0 Ω (2 turns)
15 grains - A-5
Black Powder

Surge Z_o = 50 Ω

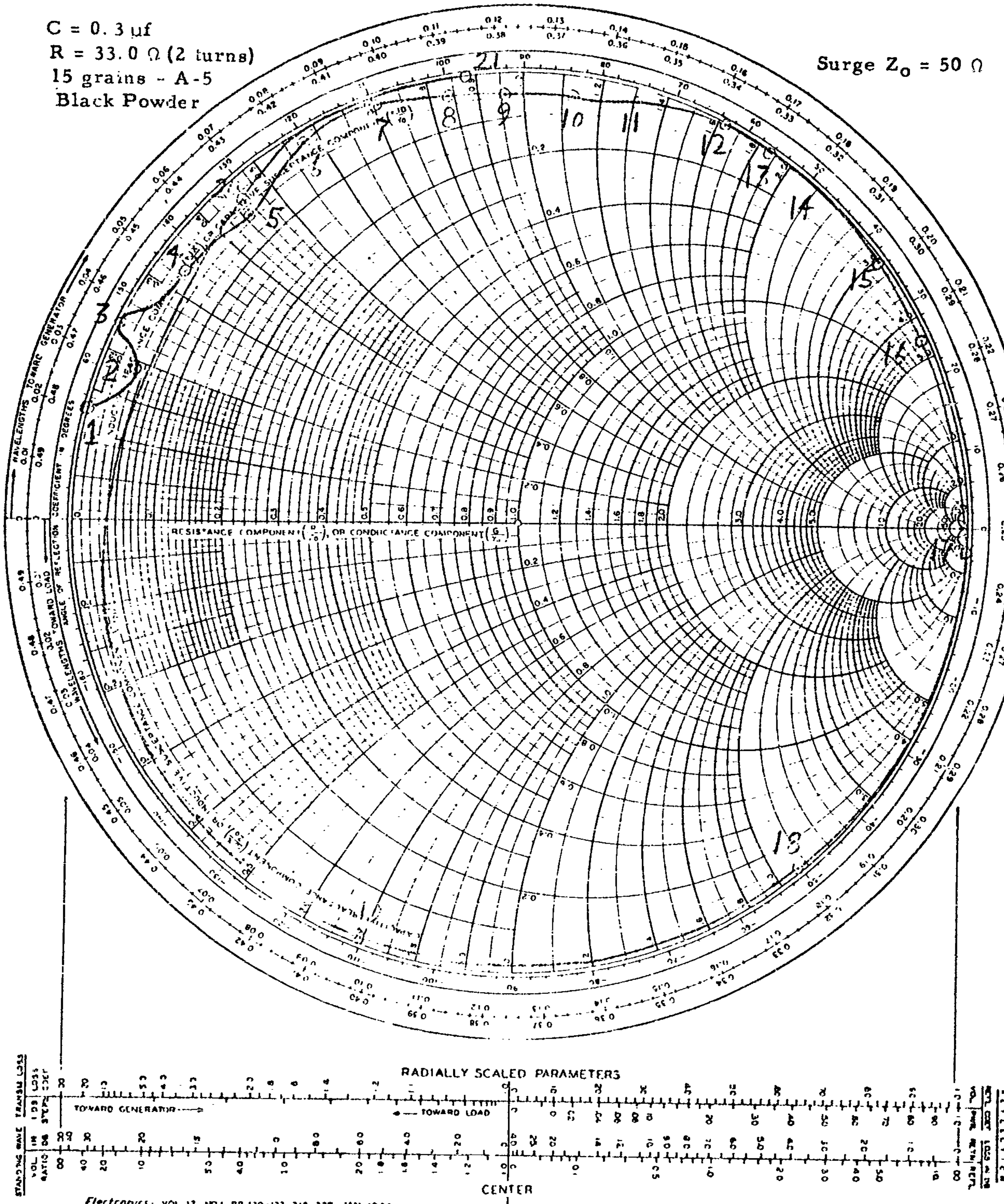


Fig. 46 - Impedance Measurements at Various Frequencies Using a Complete Squib Assembly w/American Lava Corporation Capacitance Assembly

Impedance Measurements at Various Frequencies Using a Complete Squib Assembly w/American Lava Corporation Production Model Cylindrical Titanate Capacitance Assembly (cluster of three (3) units), One (1) Turn of Bridge Wire, ten (10) grains of A-5 Black Powder, Lead Styphnate Bead Mix, Insulating Vinyl Tubing, and Hermetic Seal.

$C = 0.3\ \mu f$
$R = 23.0\ \Omega$

Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No.	Z_L (Ω)
50	1	0 + j 6.5
70	2	1.5 + j 9.5
100	3	2.5 + j 10.5
150	4	0 + j 19.5
200	5	2.0 + j 24.5
250	6	2.0 + j 30.0
300	7	3.0 + j 36.0
350	8	2.5 + j 45.0
400	9	2.5 + j 52.5
450	10	2.5 + j 62.5
500	11	1.0 + j 71.5
550	12	2.5 + j 80.5
600	13	0 + j 110.5
650	14	0 + j 150.0
700	15	0 + j 225.0
750	16	0 + j 1250.0
800	17	0 - j 250.0
850	18	0 - j 435.0
900	19	0.5 - j 0
950	20	0 + j 23.0
1000	21	0 + j 29.5

Table XXXV

IMPEDANCE OR ADMITTANCE COORDINATES

C = 0.3 uf
R = 23.0 Ω (1 turn)
10 grains - A-5
Black Powder

Surge Z_o = 50 Ω

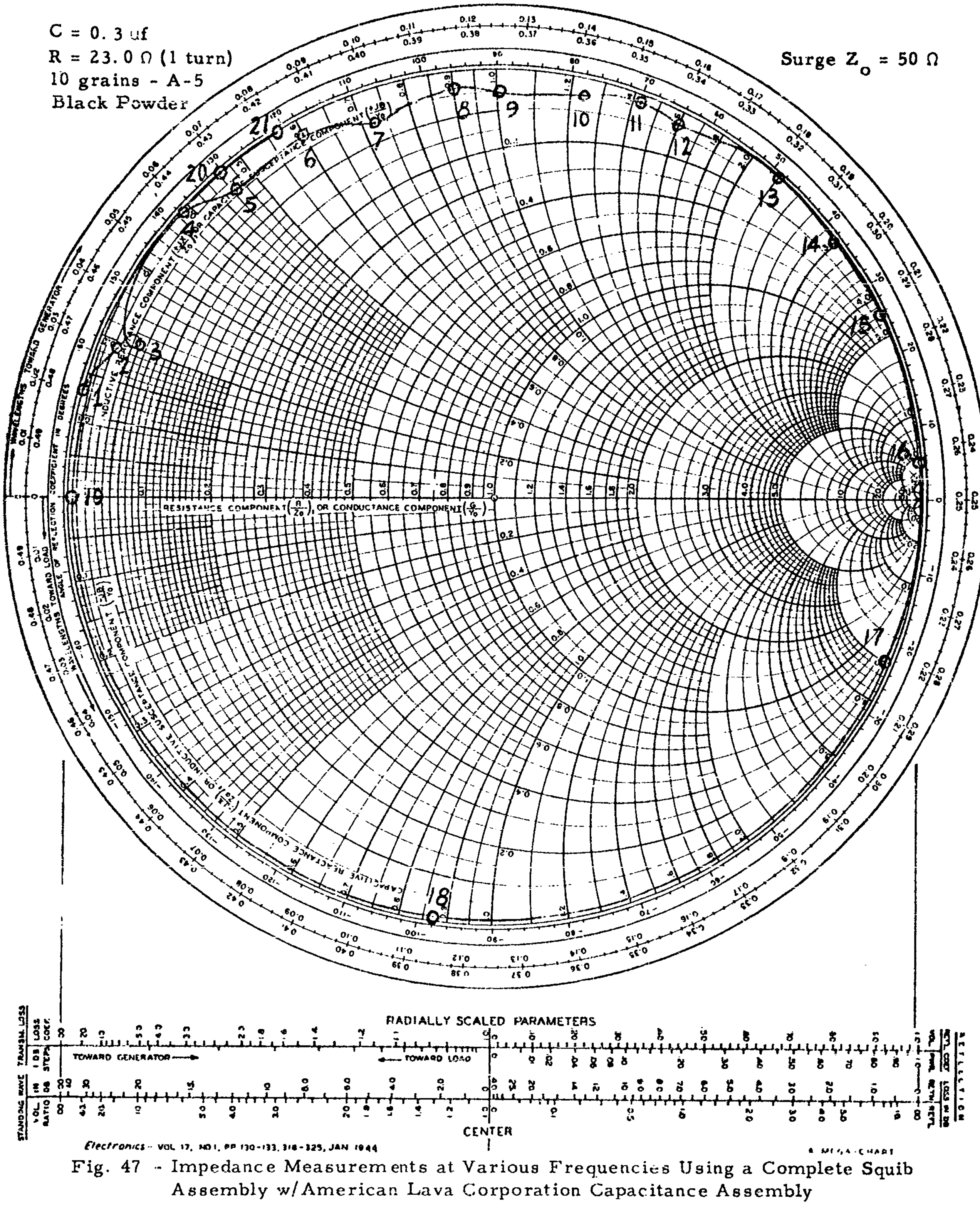


Fig. 47 - Impedance Measurements at Various Frequencies Using a Complete Squib Assembly w/American Lava Corporation Capacitance Assembly

Impedance Measurements at Various Frequencies Using a Complete Squib Assembly w/American Lava Corporation Production Model Cylindrical Titanate Capacitance Assembly (cluster of three (3) units), Two (2) Turns of Bridge Wire, ten (10) grains of A-5 Black Powder, Lead Styphnate Bead Mix, Insulating Vinyl Tubing, and Hermetic Seal.

$C = 0.3\ \mu f$
$R = 36.0\ \Omega$

Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No.	Z_L (Ω)
50	1	0 + j 7.5
70	2	2.0 + j 10.0
100	3	1.0 + j 12.5
150	4	1.0 + j 18.5
200	5	0.5 + j 24.5
250	6	1.0 + j 31.5
300	7	1.5 + j 39.5
350	8	1.0 + j 48.0
400	9	0.5 + j 57.5
450	10	0 + j 70.5
500	11	0.5 + j 86.5
550	12	0 + j 110.0
600	13	2.5 + j 165.0
650	14	5.0 + j 595.0
700	15	2.5 - j 150.0
750	16	0.5 - j 27.0
800	17	0 - j 11.5
850	18	0 + j 34.0
900	19	1.0 + j 51.0
950	20	0.5 + j 64.0
1000	21	5.0 + j 86.5

Table XXXVI

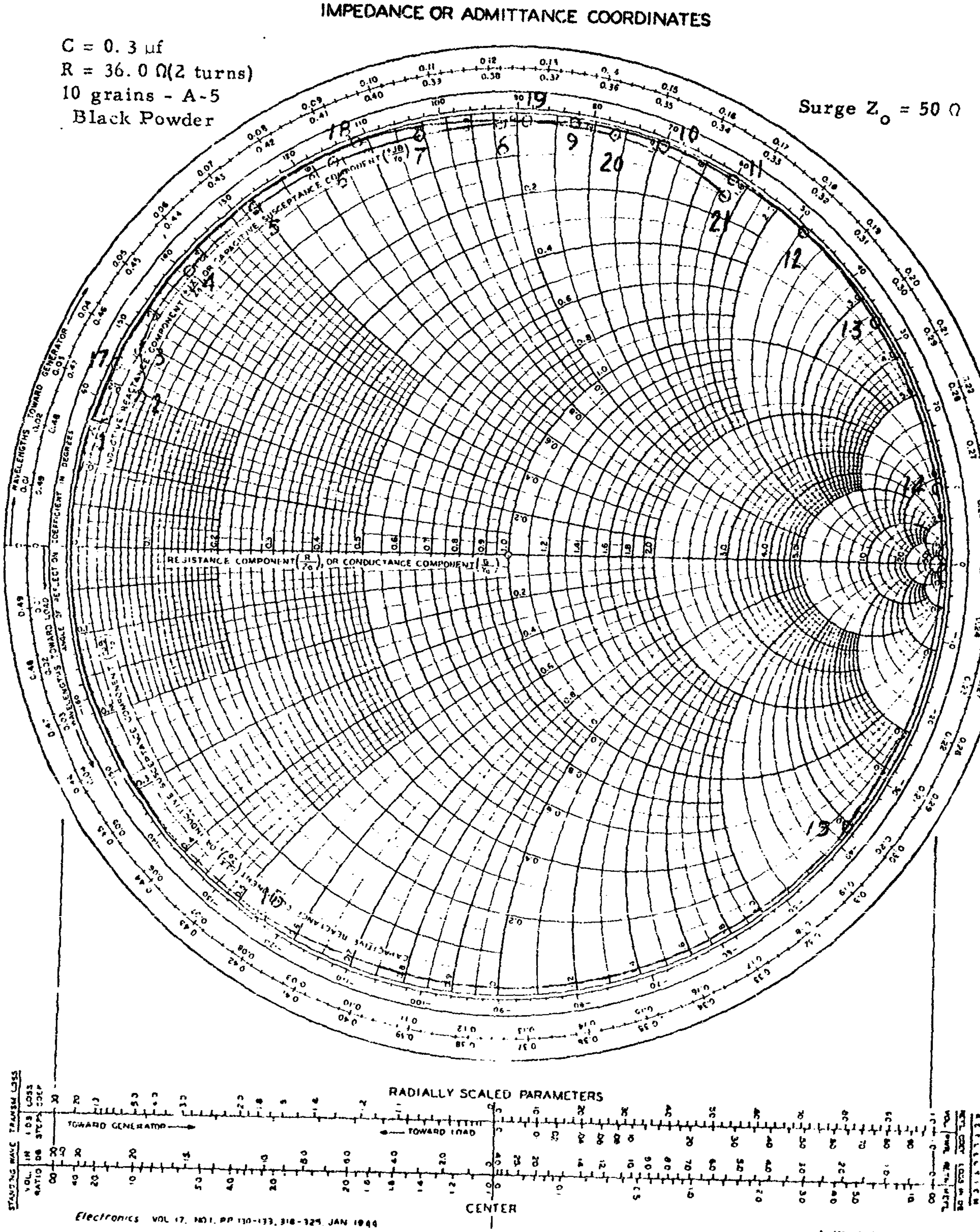


Fig. 48 - Impedance Measurements at Various Frequencies Using a Complete Squib Assembly w/American Lava Corporation Capacitance Assembly

Impedance Measurements at Various Frequencies Using a Complete Squib Assembly w/American Lava Corporation Production Model Cylindrical Titanate Capacitance Assembly (cluster of three (3) units), One (1) Turn of Bridge Wire, five (5) grains of A-5 Black Powder, Lead Styphnate Bead Mix, Insulating Vinyl Tubing, and Hermetic Seal.

C = 0.[illegible] μf
R = 16.0 Ω

Surge Z_o = 50 Ω

Frequency (mc)	Point No.	Z_L (Ω)
50	1	0 + j 6.0
70	2	1.5 + j 8.5
100	3	0 + j 10.0
150	4	0.5 + j 16.0
200	5	1.0 + j 20.0
250	6	0.5 + j 26.5
300	7	0.5 + j 32.0
350	8	1.0 + j 38.0
400	9	0 + j 45.0
450	10	0 + j 55.0
500	11	0 + j 60.0
550	12	0 + j 69.0
600	13	0 + j 89.5
650	14	0 + j 99.5
700	15	0.5 + j 126.0
750	16	4.5 + j 185.0
800	17	2.5 + j 450.0
850	18	2.5 + j 375.0
900	19	2.5 - j 62.5
950	20	2.5 - j 16.0
1000	21	0 + j 14.5

Table XXXVII

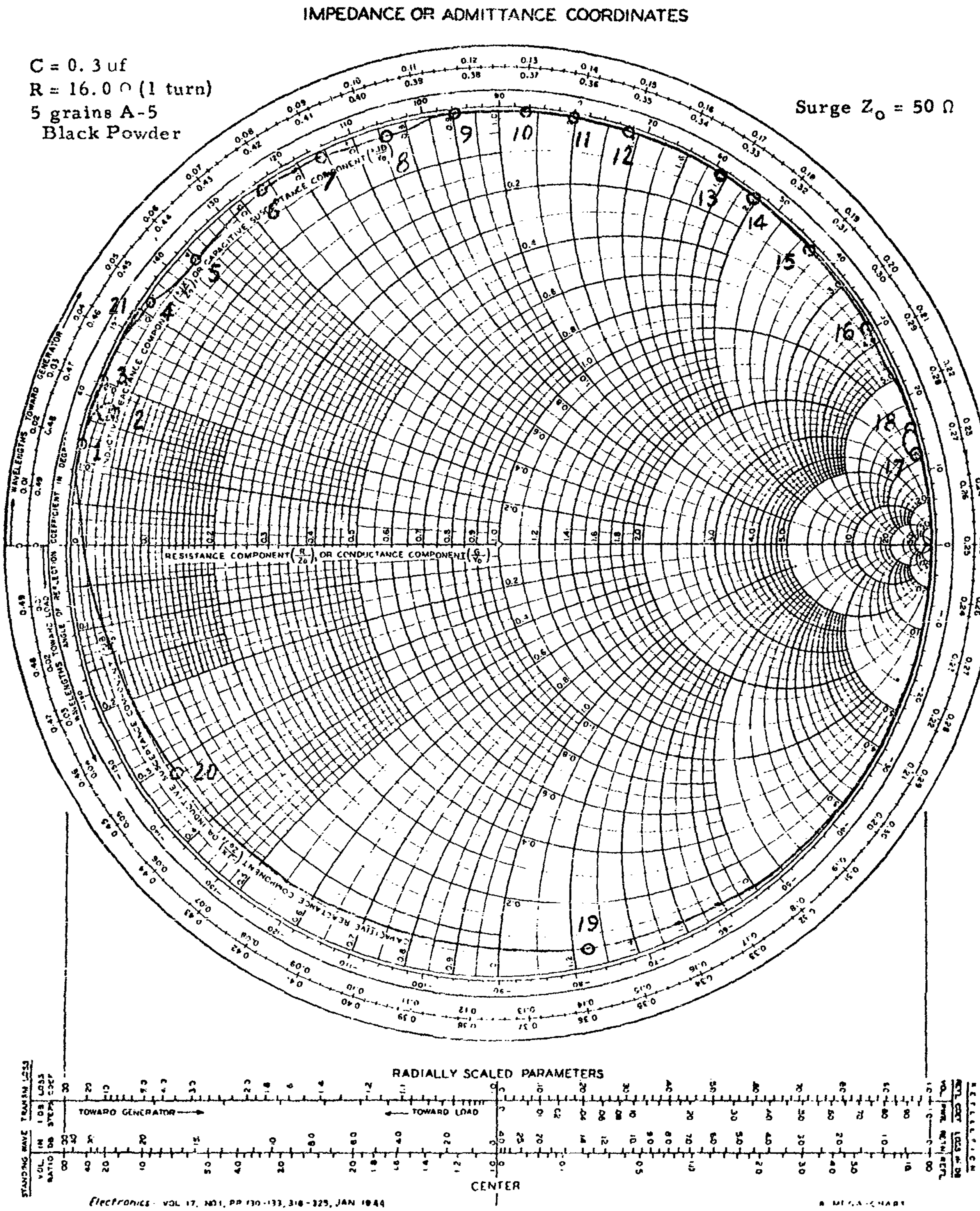


Fig. 49 - Impedance Measurements at Various Frequencies Using a Complete Squib Assembly w/American Lava Corporation Capacitance Assembly

Impedance Measurements at Various Frequencies Using a Complete Squib Assembly w/American Lava Corporation Production Model Cylindrical Titanate Capacitance Assembly (cluster of three (3) units), Two (2) Turns of Bridge Wire, five (5) grains of A-5 Black Powder, Lead Styphnate Bead Mix, Insulating Vinyl Tubing, and Hermetic Seal.

$C = 0.3\ \mu f$ $\quad$ Surge $Z_o = 50\ \Omega$

$R = 32.0\ \Omega$

Frequency (mc)	Point No.	Z_L (Ω)
50	1	0 + j 6.5
70	2	3.0 + j 8.5
100	3	1.5 + j 10.0
150	4	2.5 + j 15.0
200	5	0.5 + j 22.5
250	6	0.5 + j 28.5
300	7	0.5 + j 34.5
350	8	0.5 + j 42.0
400	9	1.5 + j 43.5
450	10	0 + j 57.5
500	11	0 + j 65.0
550	12	0 + j 75.0
600	13	0 + j 91.5
650	14	0 + j 105.0
700	15	0 + j 135.0
750	16	0 + j 180.0
800	17	0 + j 350.0
850	18	0 - j 1500.0
900	19	0 - j 79.5
950	20	0 - j 11.5
1000	21	0 - j 0

Table XXXVIII

IMPEDANCE OR ADMITTANCE COORDINATES

C = 0.3 μf
R = 32.0 Ω (2 turns)
5 grains - A-5
Black Powder

Surge Z_o = 50 Ω

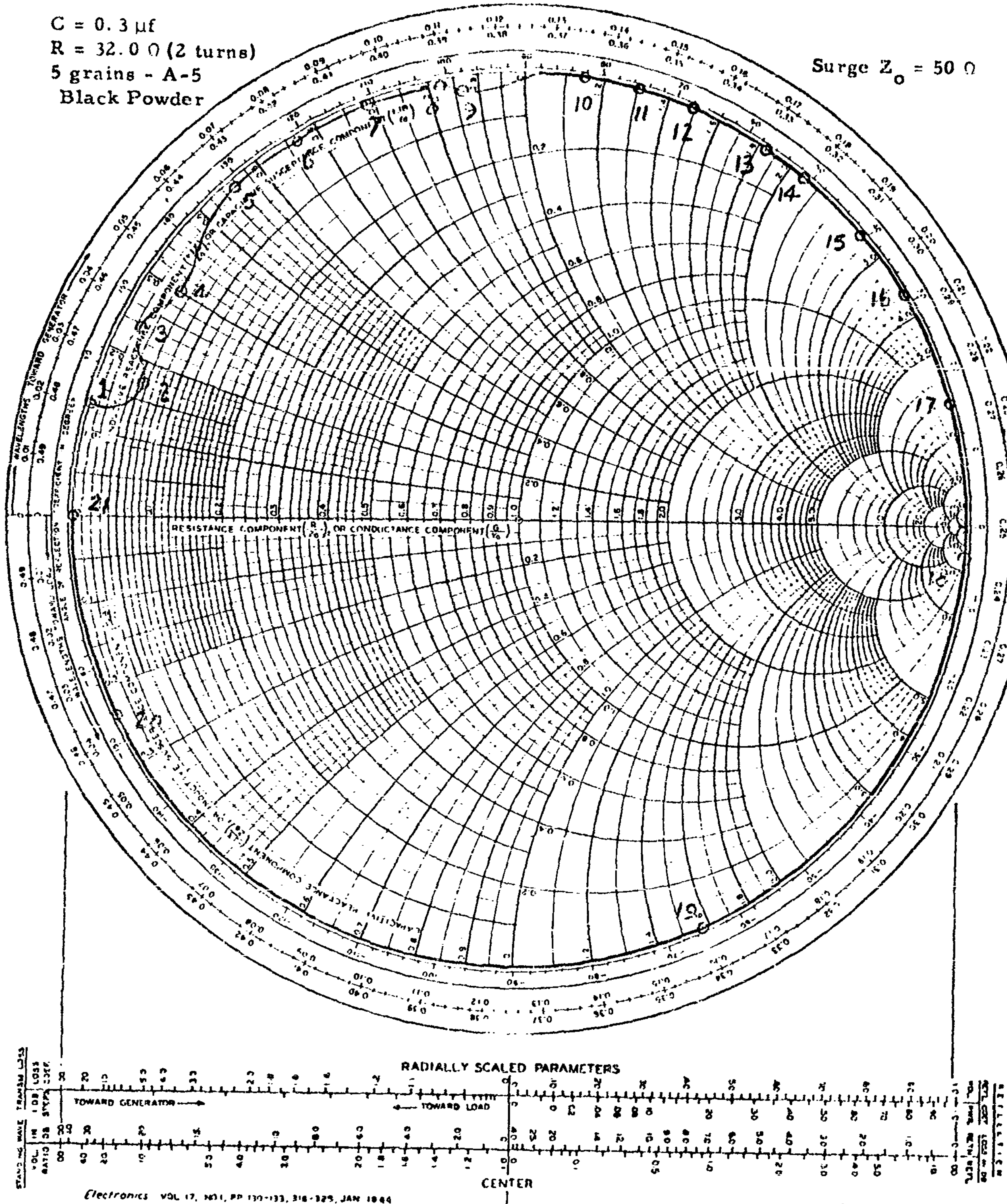


Fig. 50 - Impedance Measurements at Various Frequencies Using a Complete Squib Assembly w/American Lava Corporation Capacitance Assembly

Diode Detector Calibration Curve

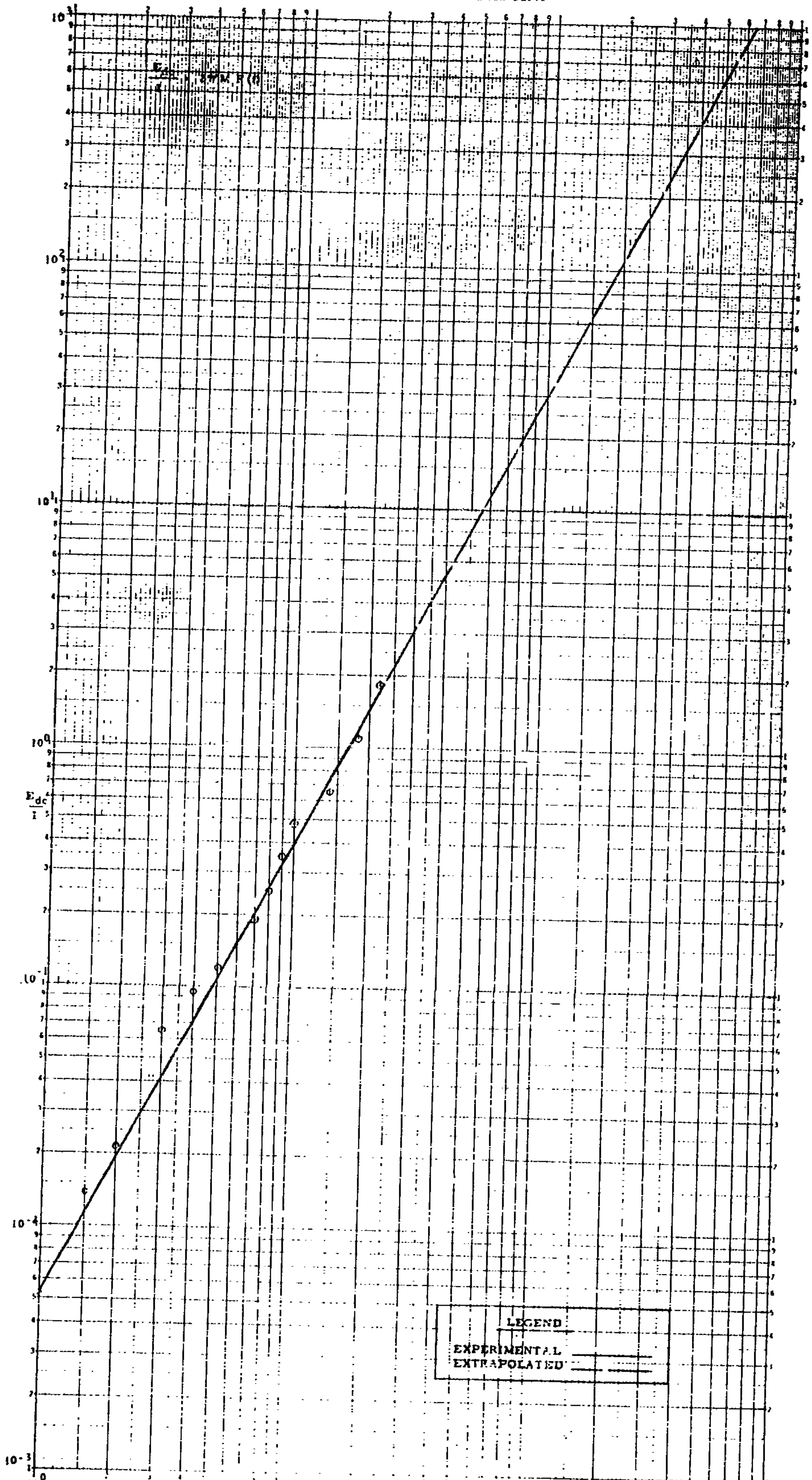


Figure 51

Histographic Representation Data Pertinent to the Degrees of Insensitization to Radio-Frequency Influences Imparted to Squibs by Capacitance Units.

The Histogram is based upon data obtained from squibs incorporating Erie Resistor Corporation elements.

$C \approx 0.5$ uf; Bridge Wire One (1) Turn; Bead Mix Lead Styphnate; Explosive-15 grains of A-5 Black Powder.

Frequency (mc)	$\frac{I}{I_o}$	$N_{db} = 20 \log_{10}\left(\frac{I}{I_o}\right)$
0.15	3.33	10.45
0.3	6.67	16.50
0.5	16.67	24.40
1.0	16.67	24.40
1.5	16.67	24.40
2.0	105.00	40.40
4.0	17.60	24.90
6.0	15.50	23.80
8.0	12.81	22.20
10.0	12.81	22.20
14.0	34.70	30.80
18.0	11.48	21.20
22.0	13.71	22.75
26.0	9.43	19.32
34.0	20.50	26.21
42.0	19.05	25.60

Table XXXIX

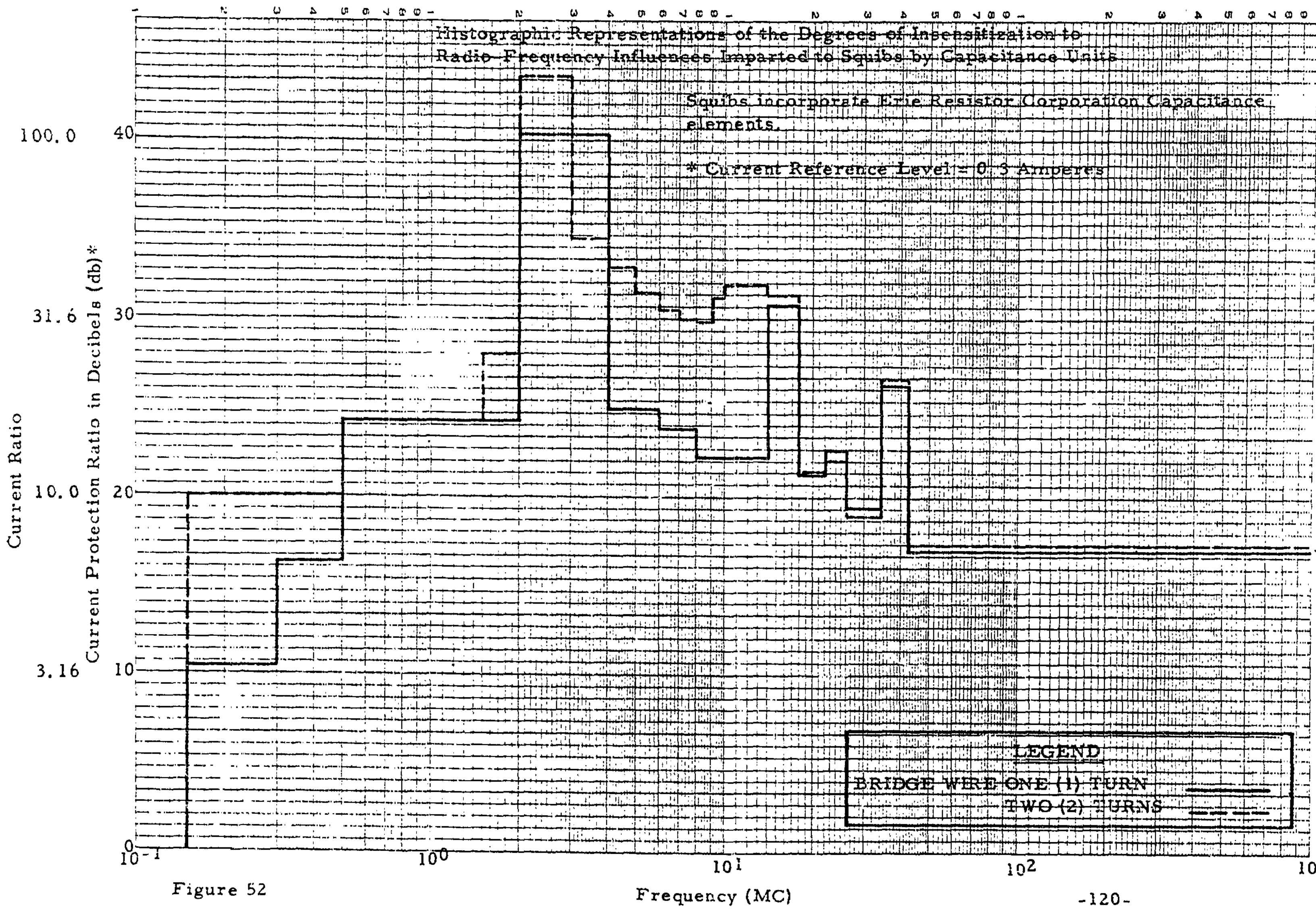
Histographic Representation Data Pertinent to the Degrees of Insensitization to Radio-Frequency Influences Imparted to Squibs by Capacitance Units.

The Histogram is based upon data obtained from squibs incorporating Erie Resistor Corporation elements.

$C \approx 0.5\ \mu f$; Bridge Wire Two (2) Turns ; Bead Mix Lead Styphnate; Explosive - 15 grains of A-5 Black Powder

Frequency (mc)	$\frac{I}{I_o}$	$N_{db} = 20 \log_{10} \left(\frac{I}{I_o} \right)$
0.15	10.00	20.00
0.3	10.00	20.00
0.5	16.67	24.40
1.0	16.67	24.40
1.5	25.00	28.00
2.0	152.60	43.60
3.0	52.50	34.40
4.0	43.90	32.89
5.0	37.30	31.45
6.0	33.30	30.45
7.0	31.66	30.00
8.0	30.80	29.80
9.0	36.50	31.20
10.0	39.30	31.90
14.0	36.60	31.25
18.0	11.80	21.43
22.0	12.75	22.10
26.0	8.70	18.80
34.0	21.35	26.40
42.0	19.65	25.90

Table XL



Histographic Representations of the Degrees of Insensitization to Radio-Frequency Influences Imparted to Squibs by Capacitance Units
Squibs incorporate Erie Resistor Corporation Capacitance elements.
* Current Reference Level = 0.3 Amperes
Current Ratio
100.0
31.6
10.0
3.16
Current Protection Ratio in Decibels (db)*
40
30
20
10
0
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Frequency (MC)
LEGEND
BRIDGE WIRE ONE (1) TURN
TWO (2) TURNS

Figure 52

Histographic Representation Data Pertinent to the Degrees of Insensitization to Radio-Frequency Influences Imparted to Squibs by Capacitance Units.

The Histogram is based upon data obtained from squibs incorporating American Lava Corporation elements.

C = 0.3 μf; Bridge Wire One (1) Turn; Bead Mix Lead Styphnate; Explosive - 15 grains of A-5 Black Powder

Frequency (mc)	$\frac{I}{I_o}$	$N_{db} = 20 \log_{10}\left(\frac{I}{I_o}\right)$
0.15	3.33	10.46
0.3	6.67	16.50
0.5	16.67	24.47
1.0	16.67	24.47
1.5	25.00	27.90
2.0	105.00	40.40
3.0	108.00	40.70
4.0	89.1	39.00
5.0	30.2	29.80
6.0	27.1	28.65
7.0	26.3	28.40
8.0	23.1	27.30
9.0	22.9	27.20
10.0	26.4	28.70
14.0	43.4	32.70
18.0	27.8	28.90
22.0	21.6	26.70
29.0	13.8	22.80
34.0	17.5	24.90
38.0	11.1	20.90
42.0	5.92	15.45

Table XLI

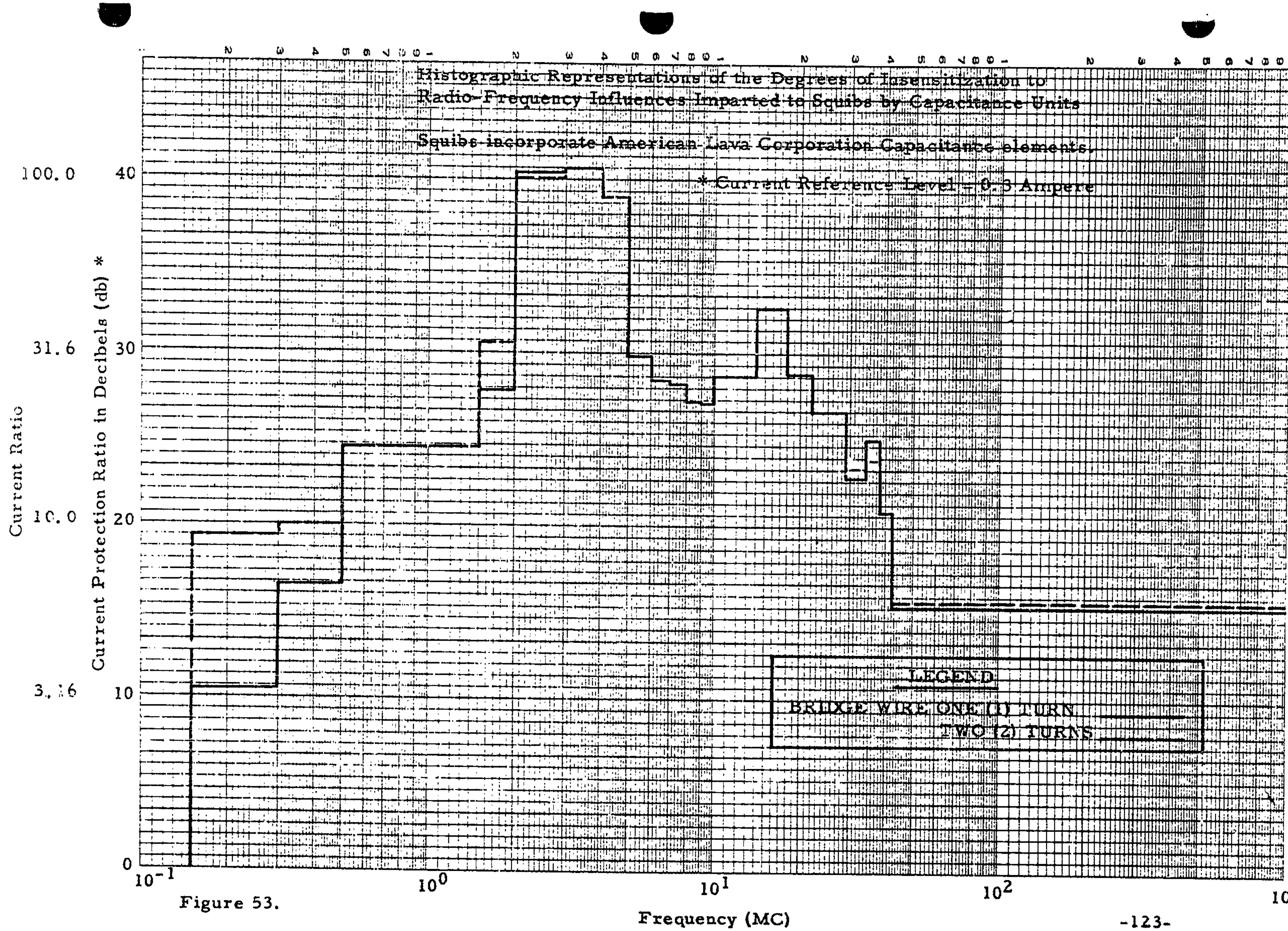
Histographic Representation Data Pertinent to the Degrees of Insensitization to Radio-Frequency Influences Imparted to Squibs by Capacitance Units.

The Histogram is based upon data obtained from squibs incorporating American Lava Corporation elements.

C = 0.3 μf; Bridge Wire Two (2) Turns; Bead Mix Lead Styphnate; Explosive - 15 grains of A-5 Black Powder

Frequency (mc)	$\frac{I}{I_o}$	$N_{db} = 20 \log_{10}\left(\frac{I}{I_o}\right)$
0.15	9.30	19.35
0.3	10.00	20.00
0.5	16.70	24.45
1.0	16.70	24.45
1.5	33.30	30.42
2.0	101.70	40.10
3.0	107.30	40.60
4.0	88.60	39.00
5.0	30.15	29.60
6.0	27.10	28.65
7.0	26.30	28.40
8.0	23.10	27.30
9.0	22.90	27.20
10.0	27.20	28.70
14.0	43.40	32.70
18.0	27.80	28.90
22.0	21.60	26.70
29.0	14.80	23.40
34.0	15.40	23.80
38.0	11.10	20.90
42.0	6.04	15.55

Table XLII



Histographic Representations of the Degrees of Insensitization to
Radio-Frequency Influences Imparted to Squibs by Capacitance Units
Squibs incorporate American Lava Corporation Capacitance elements.
* Current Reference Level = 0.3 Ampere
LEGEND
BRIDGE WIRE ONE (1) TURN
TWO (2) TURNS
Current Ratio
100.0
31.6
10.0
3.16
Current Protection Ratio in Decibels (db) *
40
30
20
10
0
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
Frequency (MC)

Figure 53.

b. Microwave

These data were compiled in the microwave frequency spectrum for frequencies from 960 megacycles to 10,500 megacycles.

Tables XLIII and XLIV are tabulated values in percent of the number of squibs which could withstand the designated R.F. power levels at the indicated frequencies. The Smith Charts (Figures 54 through 61) reveal the resultant change in impedance of the squib as the incident R.F. power level is increased. Figures 62 through 65 reveal the voltage standing wave ratio versus frequency at a one watt incident power level. A study in greater detail of the impedance characteristics versus frequency is shown by Figure 66 which is a Smith Chart.

Frequency (mc)	% of Squibs fabricated from American Lava Corporation elements - Bridge Wire Two (2) Turns which were detonated by the tabulated incident power levels (watts)* (application time of signal - = 30.0 sec.)							
	20	25	30	40	50	60	75	100
960							(100)	NA
1,470	30					35	(35)	NA
5,000			75				20	(5)
5,500	83		7	10				
6,000	52					46		(2)
8,650		62			15		(23)	NA
9,500	86	7			4		(3)	NA
10,500	60	5			30		(5)	NA

* - Minimum Number of squibs tested at each frequency - 10

NA - Not Available

( ) - Indicates % of squibs not detonated

Table XLIII

Frequency (mc)	% of Squibs fabricated from American Lava Corporation elements - Bridge Wire One (1) Turn which were detonated by the tabulated incident power levels (watts)* (application time of signal = 30.0 sec.)							
	20	25	30	40	50	60	75	100
960							(100)	NA
1,470							(100)	NA
5,000	34	66						
5,500	34		66					
6,000		40	45	15				
8,650		24			38		(38)	NA
9.500		62			8		(30)	NA
10,500	83	7			10			NA

* - Minimum Number of squibs tested at each frequency - 10

NA - Not Available

( ) - Indicates % of squibs not detonated.

Table XLIV

Impedance vs Radio-Frequency Power Level Using a Complete Squib Assembly incorporating American Lava Corporation elements

Frequency, f = 0.96 KMC

One (1) Turn Bridge Wire

R-F Power Level (Watts)	Point No.	Z_L (Ω)
5.0	1	2.5 + j 55.0
10.0	2	4.0 + j 56.5
15.0	3	5.0 + j 70.0
25.0	4	2.0 + j 47.0

Two (2) Turns Bridge Wire

R-F Power Level (Watts)	Point No.	Z_L (Ω)
5.0	1	600.0 - j 1000.0
10.0	2	900.0 - j 800.0
15.0	3	1500.0 - j 600.0
25.0	4	2500.0 - j 1000.0

Table XLV

IMPEDANCE OR ADMITTANCE COORDINATES

Frequency, f = 0.96 KMC

• Bridge Wire (1 Turn)

⊙ Bridge Wire (2 Turns)

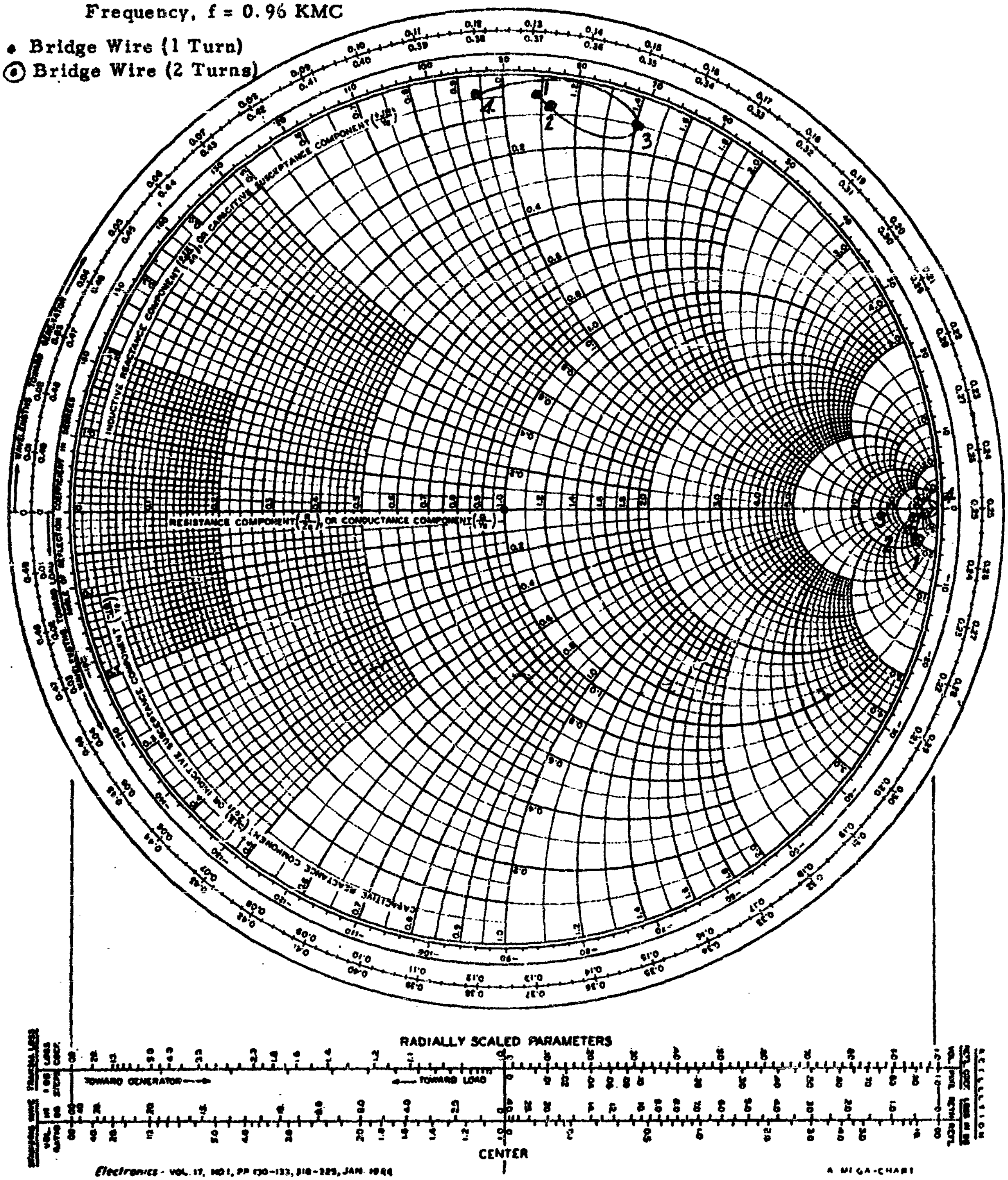


Fig. 54 - Impedance vs Radio-Frequency Power Level Using a Complete Squib Assembly incorporating American Lava Corporation elements.

Impedance vs Radio-Frequency Power Level Using a Complete Squib Assembly incorporating American Lava Corporation elements

Frequency, f = 1.47 KMC

One (1) Turn Bridge Wire

R-F Power Level (Watts)	Point No.	Z_L (Ω)
5.0	1	2.5 + j 61.5
10.0	2	2.5 + j 59.5
15.0	3	3.2 + j 58.5
25.0	4	2.5 + j 57.5

Two (2) Turns Bridge Wire

R-F Power Level (Watts)	Point No.	Z_L (Ω)
5.0	1	4.0 + j 67.5
10.0	2	6.0 + j 67.0
15.0	3	5.0 + j 63.0
25.0	4	5.0 + j 61.0

Table XLVI

Frequency, f = 1.47 KMC

• Bridge Wire (1 Turn)

○ Bridge Wire (2 Turns)

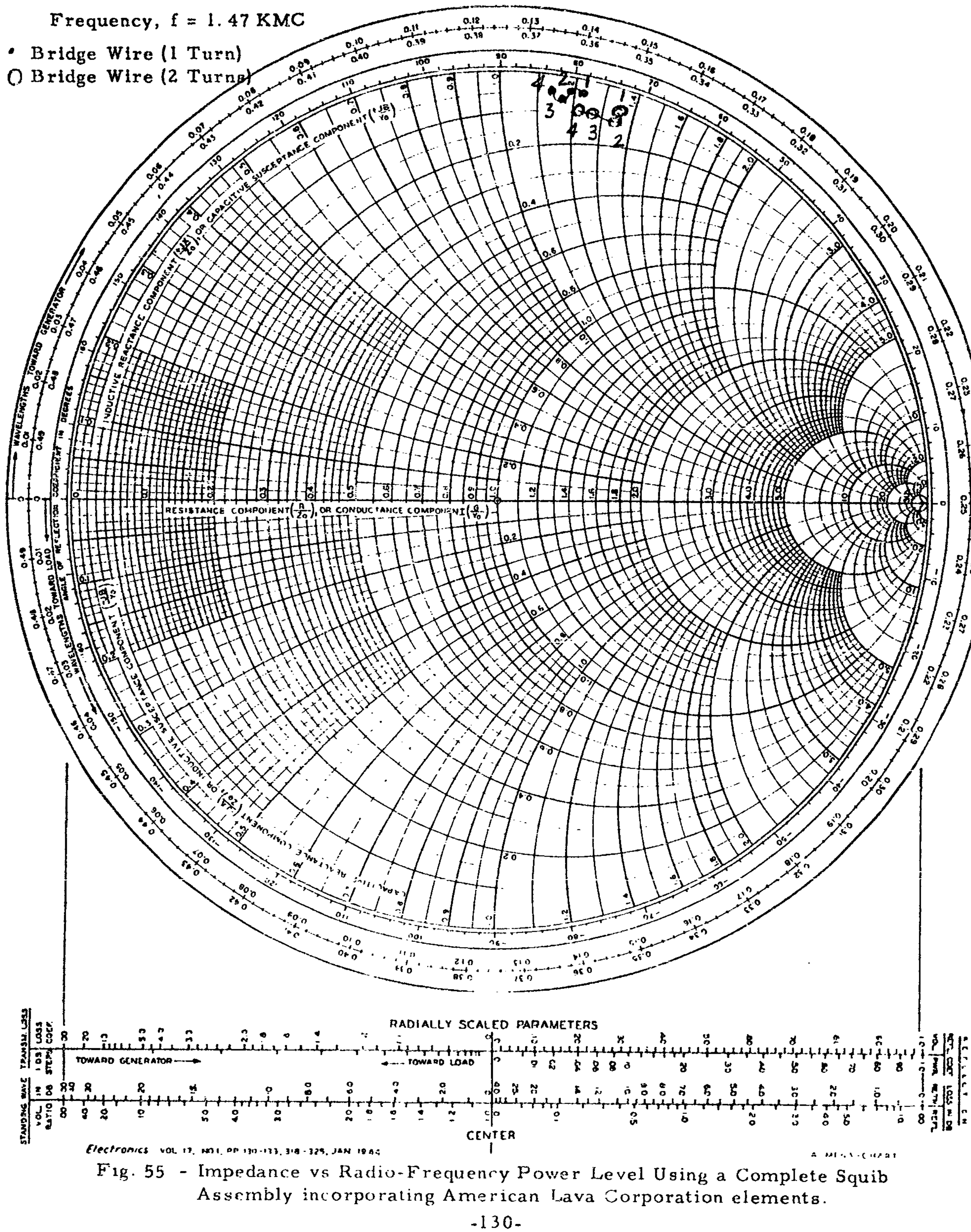


Fig. 55 - Impedance vs Radio-Frequency Power Level Using a Complete Squib Assembly incorporating American Lava Corporation elements.

Impedance vs Radio-Frequency Power Level Using A Complete Squib Assembly incorporating American Lava Corporation elements

Frequency, f = 5.0 KMC

One (1) Turn Bridge Wire

RF Power Level (Watts)	Point No.	Z_L (Ω)
5.0	1	12.0 - j 51.5
10.0	2	9.0 - j 48.5
15.0	3	7.0 - j 44.0
20.0	4	5.5 - j 40.0

Two (2) Turns Bridge Wire

RF Power Level (Watts)	Point No.	Z_L (Ω)
5.0	1	6.5 - j 9.0
10.0	2	4.5 - j 7.0
15.0	3	2.5 - j 7.0
20.0	4	2.5 - j 5.0

Table XLVII

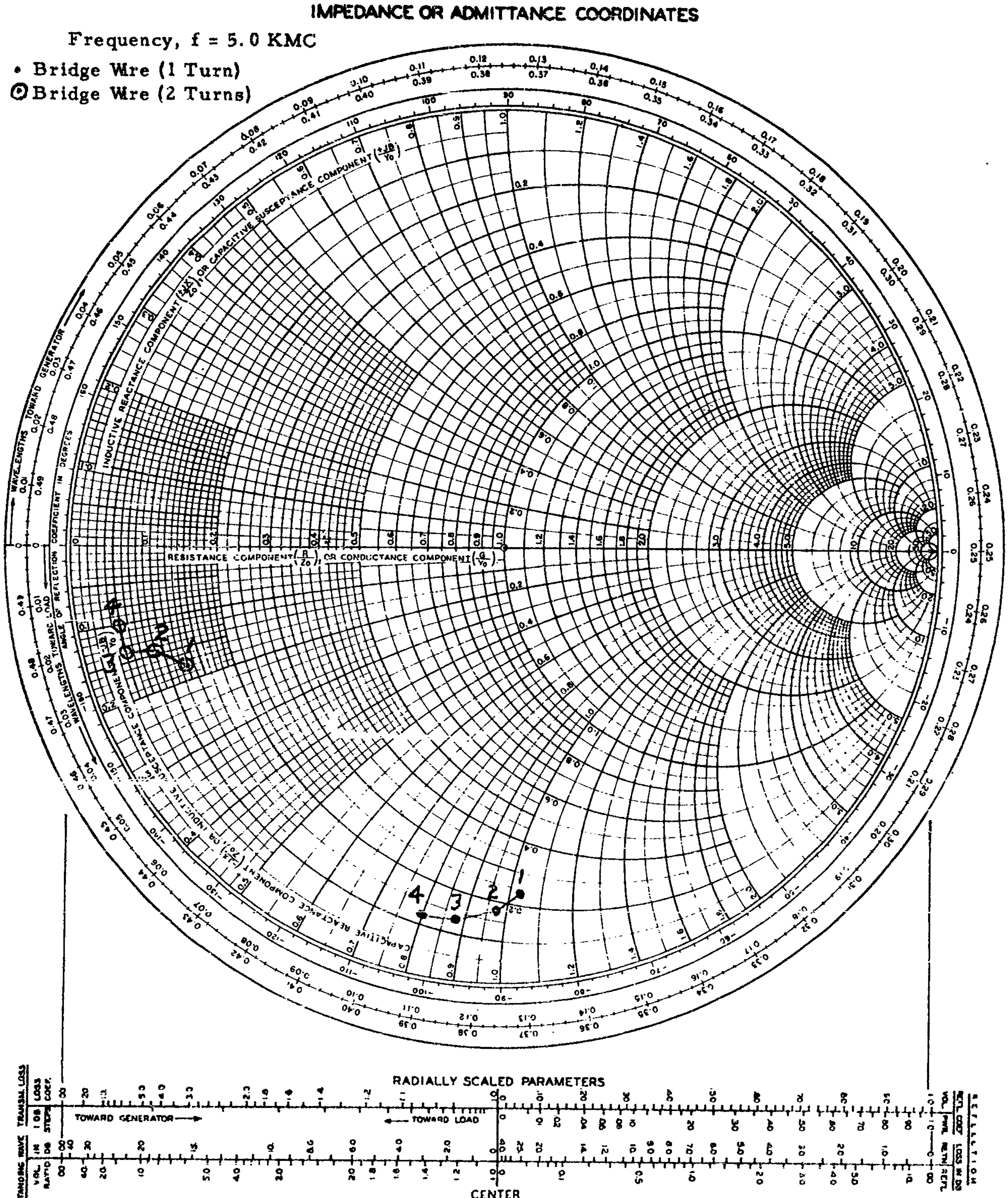


Fig. 56 - Impedance vs Radio-Frequency Power Level Using A Complete Squib Assembly incorporating American Lava Corporation elements.

Impedance vs Radio-Frequency Power Level Using a Complete Squib Assembly incorporating American Lava Corporation elements.

Frequency, f = 5.5 KMC

One (1) Turn Bridge Wire

RF Power Level (Watts)	Point No.	Z_L (Ω)
5.0	1	30.0 - j 35.0
10.0	2	25.5 - j 32.5
15.0	3	22.5 - j 30.0
20.0	4	21.0 - j 26.0

Two (2) Turns Bridge Wire

RF Power Level (Watts)	Point No.	Z_L (Ω)
5.0	1	80.0 - j 140.0
10.0	2	60.0 - j 120.0
15.0	3	40.0 - j 117.5
20.0	4	27.8 - j 110.0

Table XLVIII

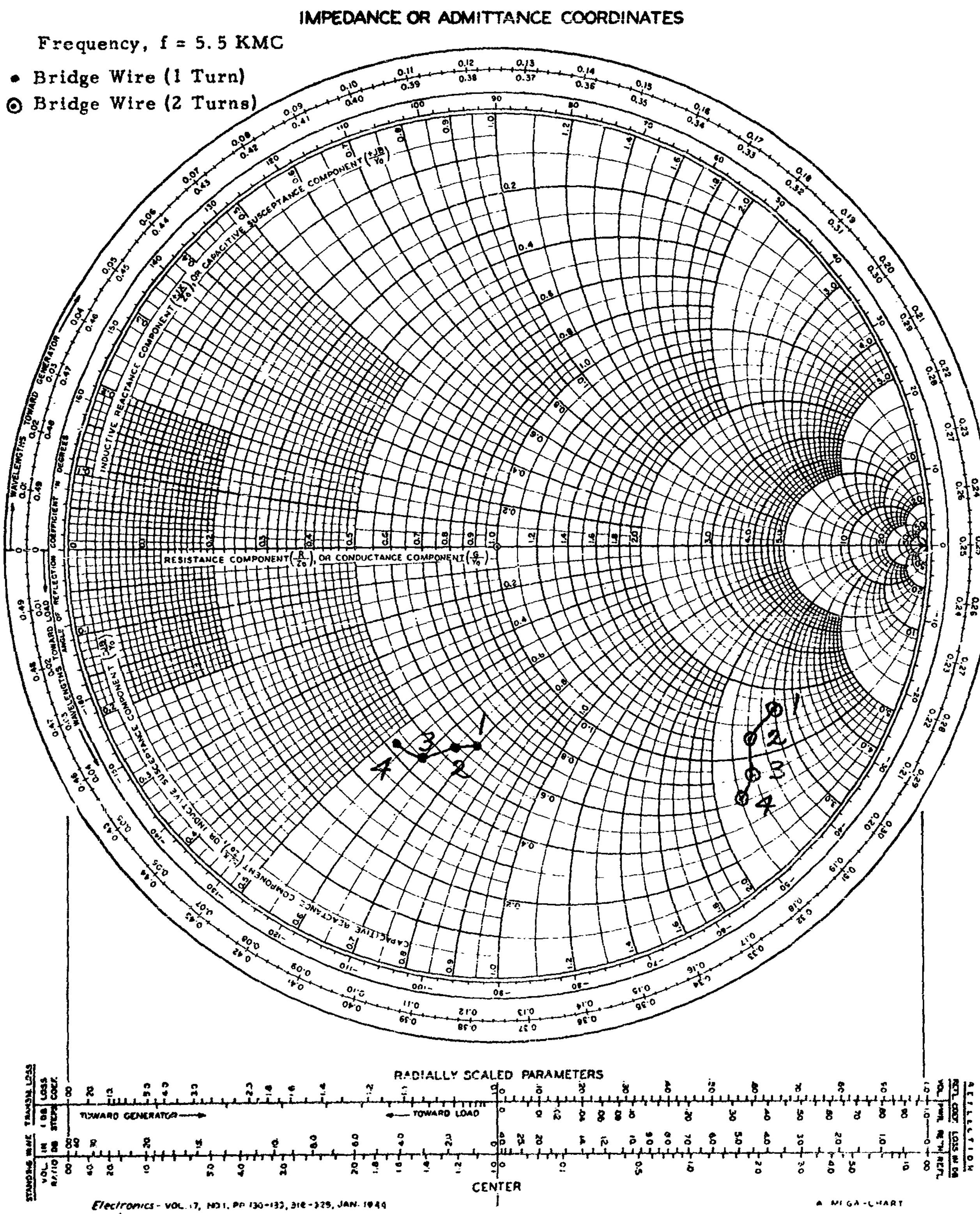


Fig. 57- Impedance vs Radio-Frequency Power Level Using a Complete Squib Assembly incorporating American Lava Corporation elements.

Impedance vs Radio-Frequency Power Level Using A Complete Squib Assembly incorporating American Lava Corporation elements

Frequency, f = 6.0 KMC

One (1) Turn Bridge Wire

RF Power Level (Watts)	Point No.	Z_L (Ω)
5.0	1	50.0 + j 165.0
10.0	2	40.0 + j 150.0
15.0	3	50.0 + j 140.0
20.0	4	50.0 + j 120.0

Two (2) Turns Bridge Wire

RF Power Level (Watts)	Point No.	Z_L (Ω)
5.0	1	800.0 - j 450.0
10.0	2	400.0 - j 550.0
15.0	3	275.0 - j 475.0
20.0	4	125.0 - j 450.0

Table XLIX

Frequency, f = 6.0 KMC

• Bridge Wire (1 Turn)

⊙ Bridge Wire (2 Turns)

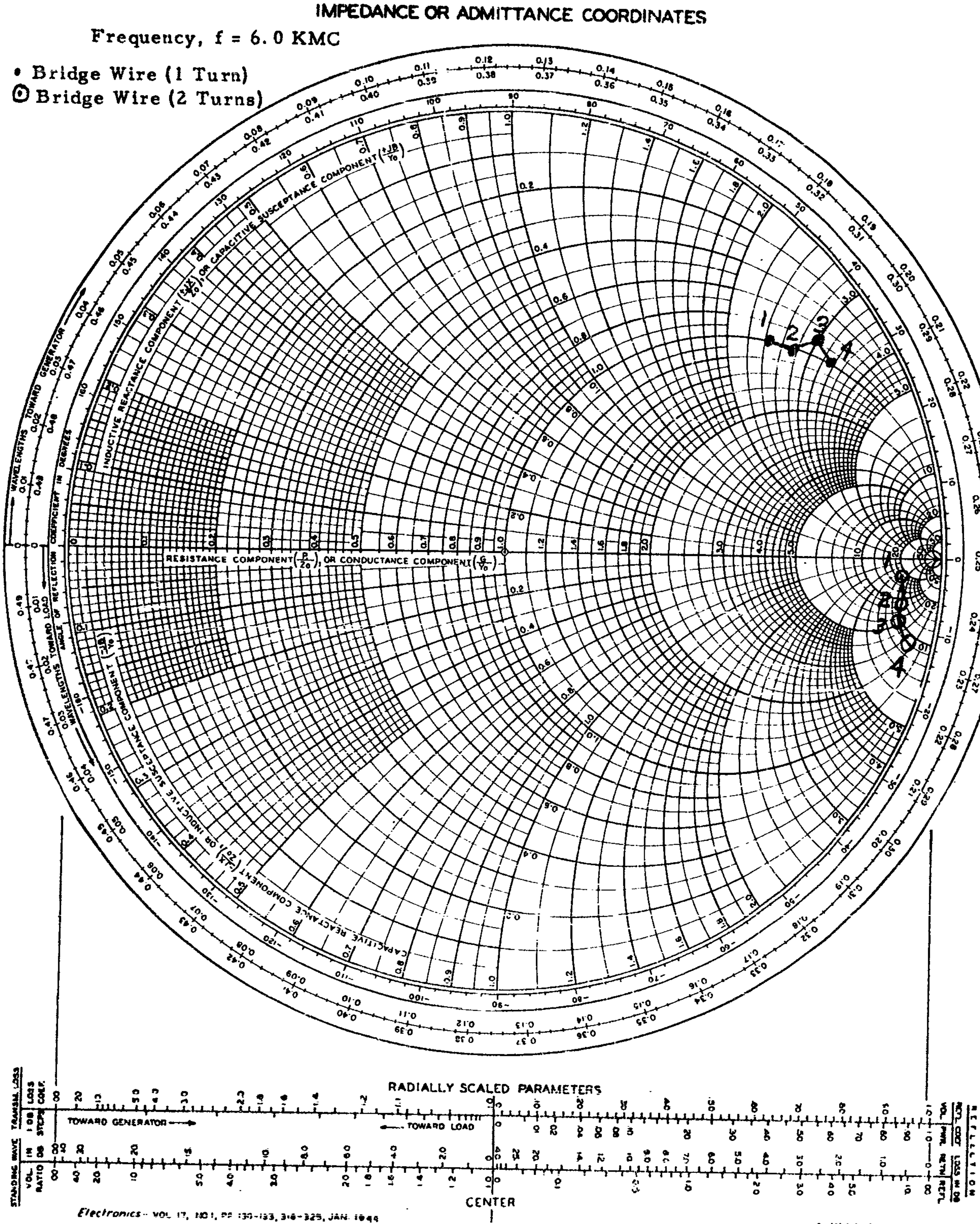


Fig. 58 - Impedance vs Radio-Frequency Power Level Using A Complete Squib Assembly incorporating American Lava Corporation elements.

Impedance vs Radio-Frequency Power Level Using a Complete Squib Assembly incorporating American Lava Corporation elements

Frequency, f = 8.65 KMC

One (1) Turn Bridge Wire

RF Power Level (Watts)	Point No.	Z_L (Ω)
5.0	1	9.0 + j 17.0
10.0	2	5.0 + j 18.0
15.0	3	3.5 + j 17.0
20.0	4	3.0 + j 16.0

Two (2) Turns Bridge Wire

RF Power Level (Watts)	Point No.	Z_L (Ω)
5.0	1	4.0
10.0	2	2.5
15.0	3	1.5
20.0	4	1.0 + j 14.3

Table L

IMPEDANCE OR ADMITTANCE COORDINATES

Frequency, f = 8.65 KMC

• Bridge Wire (1 Turn)

⊙ Bridge Wire (2 Turns)

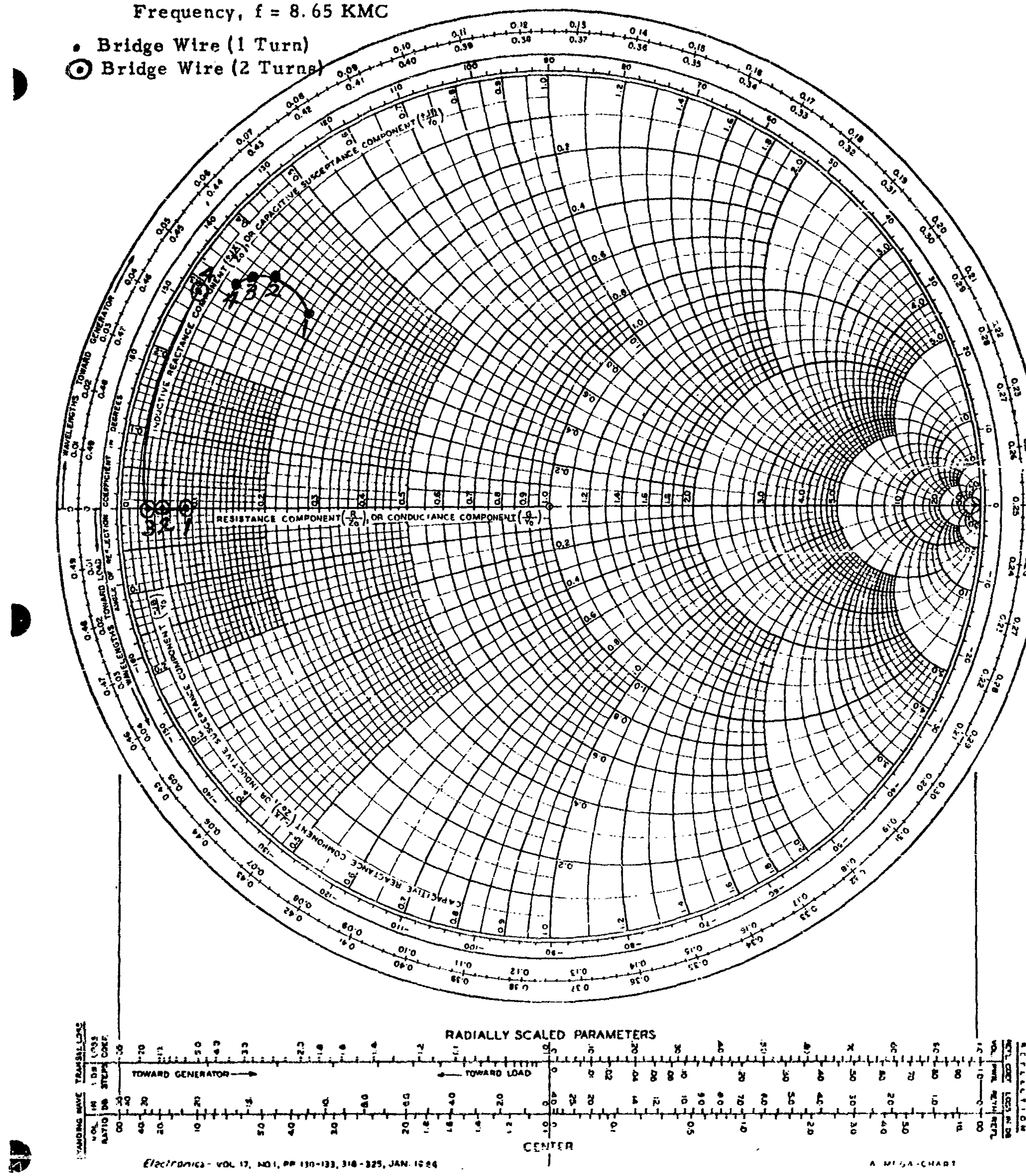


Fig. 59- Impedance vs Radio-Frequency Power Level Using a Complete Squib Assembly incorporating American Lava Corporation elements.

Impedance vs Radio-Frequency Power Level Using a Complete Squib Assembly incorporating American Lava Corporation elements

Frequency, f = 9.50 KMC

One (1) Turn Bridge Wire

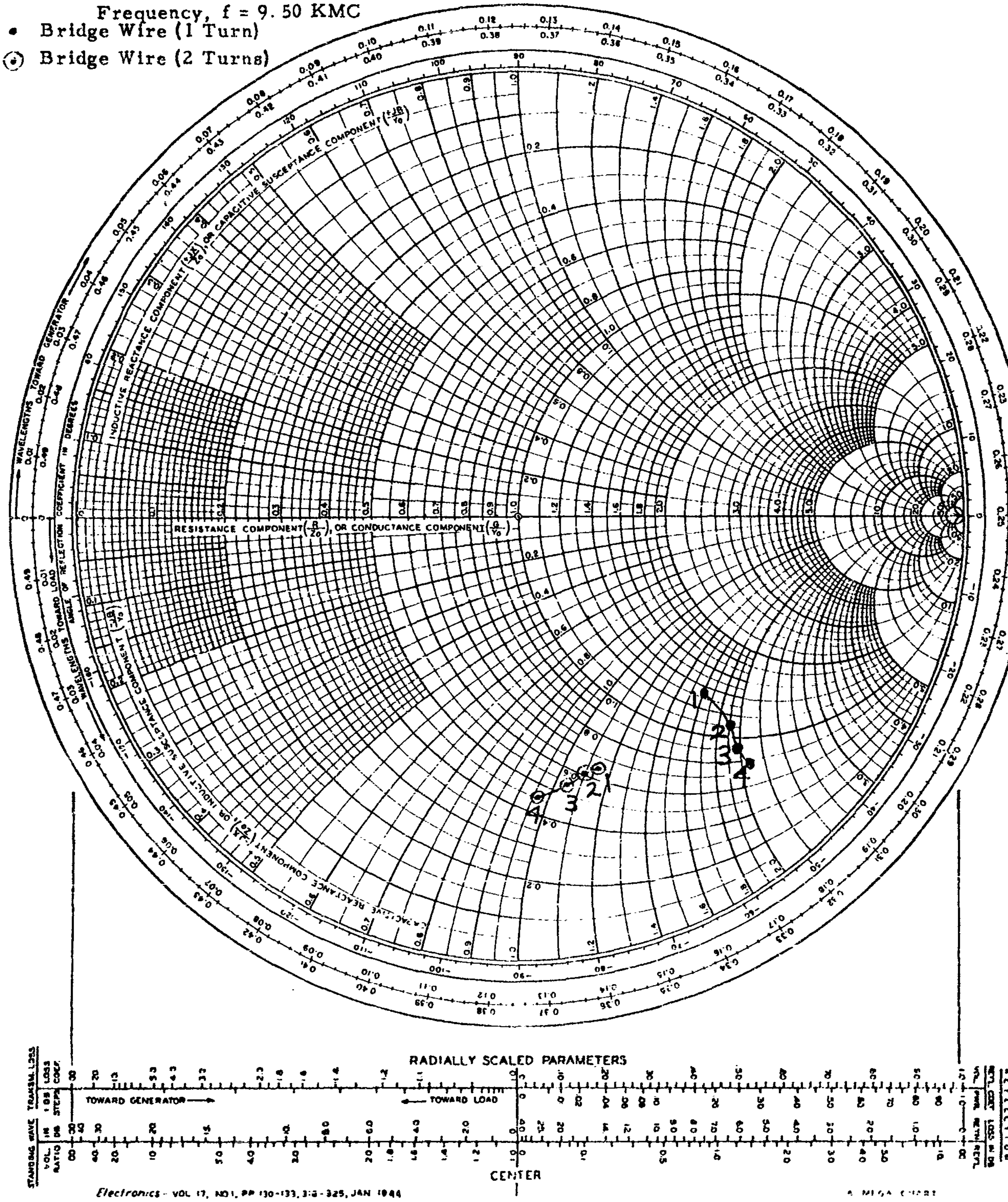
RF Power Level (Watts)	Point No.	Z_L (Ω)
5.0	1	67.6 - j 80.0
10.0	2	55.0 - j 95.0
15.0	3	45.0 - j 99.0
20.0	4	40.0 - j103.0

Two (2) Turns Bridge Wire

RF Power Level (Watts)	Point No.	Z_L (Ω)
5.0	1	32.5 - j 57.4
10.0	2	30.0 - j 55.0
15.0	3	26.2 - j 52.5
20.0	4	22.5 - j 48.0

Table LI

IMPEDANCE OR ADMITTANCE COORDINATES



'Fig. 60 - Impedance vs Radio-Frequency Power Level Using a Complete Squib Assembly incorporating American Lava Corporation elements

Impedance vs Radio-Frequency Power Level Using a Complete Squib Assembly incorporating American Lava Corporation elements

Frequency, f = 10.5 KMC

One (1) Turn Bridge Wire

RF Power Level (Watts)	Point No.	Z_L (Ω)
5.0	1	9.0 + j 9.5
10.0	2	7.5 + j 10.0
15.0	3	6.5 + j 10.5
20.0	4	6.0 + j 11.0

Two (2) Turns Bridge Wire

RF Power Level (Watts)	Point No.	Z_L (Ω)
5.0	1	27.5 + j 24.5
10.0	2	27.0 + j 25.5
15.0	3	26.0 + j 26.5
20.0	4	25.0 + j 27.5

Table LII

IMPEDANCE OR ADMITTANCE COORDINATES

Frequency, f = 10.5 KMC

▫ Bridge Wire (1 Turn)

⊙ Bridge Wire (2 Turns)

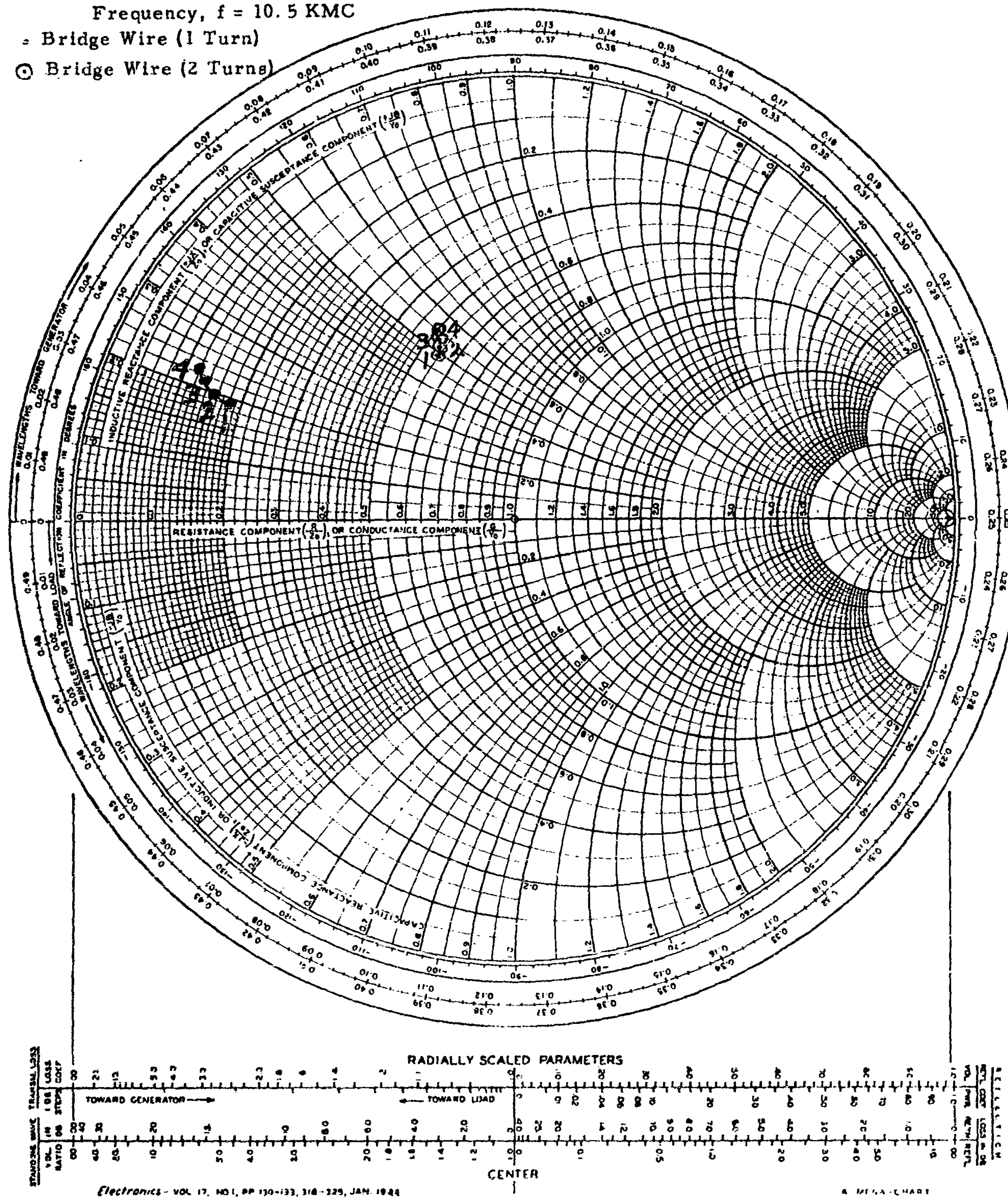
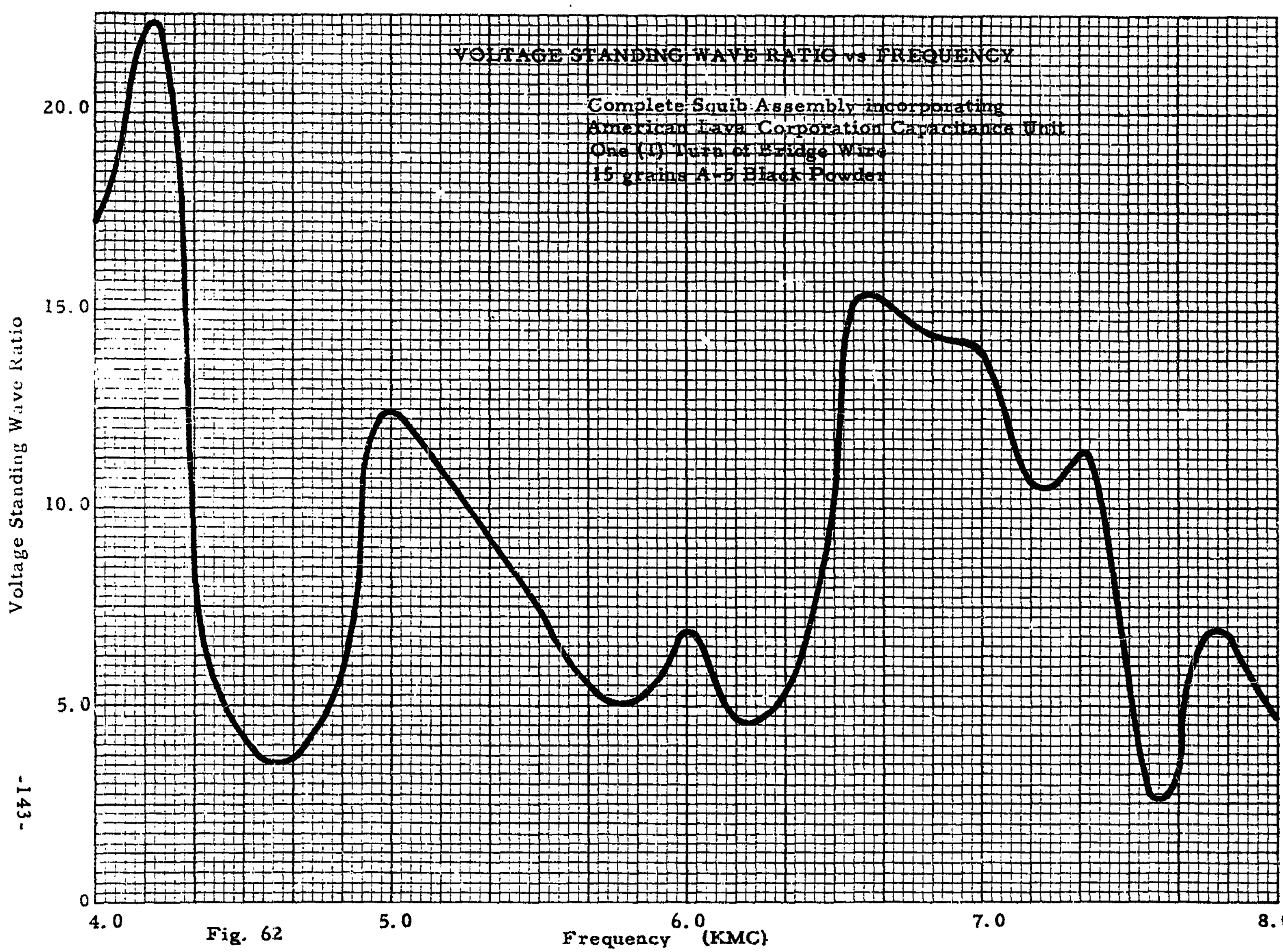


Fig. 61 - Impedance vs Radio-Frequency Power Level Using a Complete Squib Assembly incorporating American Lava Corporation elements



VOLTAGE STANDING WAVE RATIO vs FREQUENCY
Complete Squib Assembly incorporating
American Lava Corporation Capacitance Unit
One (1) Turn of Bridge Wire
15 grains A-5 Black Powder
Voltage Standing Wave Ratio
20.0
15.0
10.0
5.0
0
4.0
5.0
6.0
7.0
8.0
Frequency (KMC)

Fig. 62

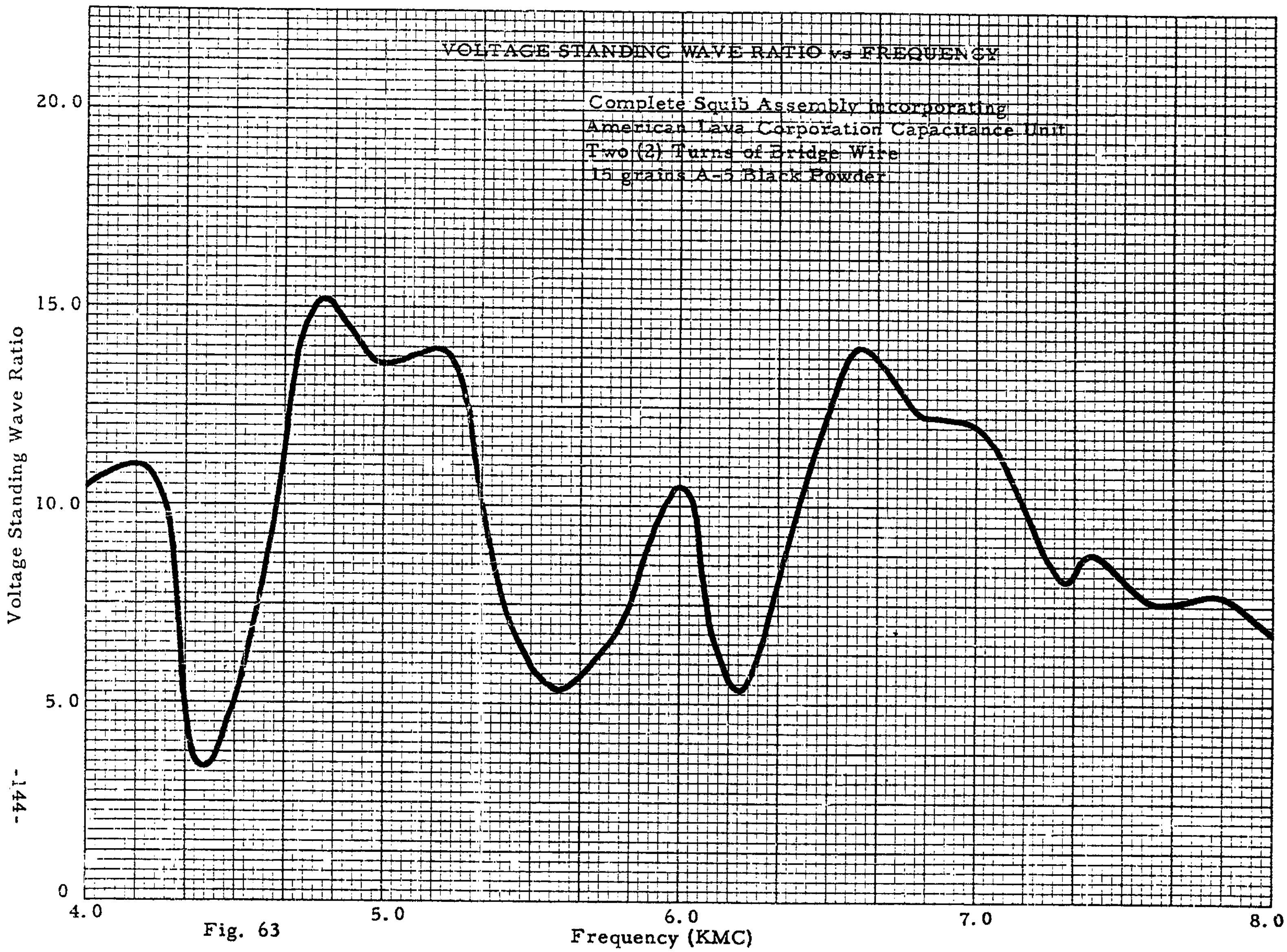

VOLTAGE STANDING WAVE RATIO vs FREQUENCY
Complete Squib Assembly incorporating
American Lava Corporation Capacitance Unit
Two (2) Turns of Bridge Wire
15 grains A-5 Black Powder
Voltage Standing Wave Ratio
20.0
15.0
10.0
5.0
0
4.0
5.0
6.0
7.0
8.0
Frequency (KMC)

Fig. 63

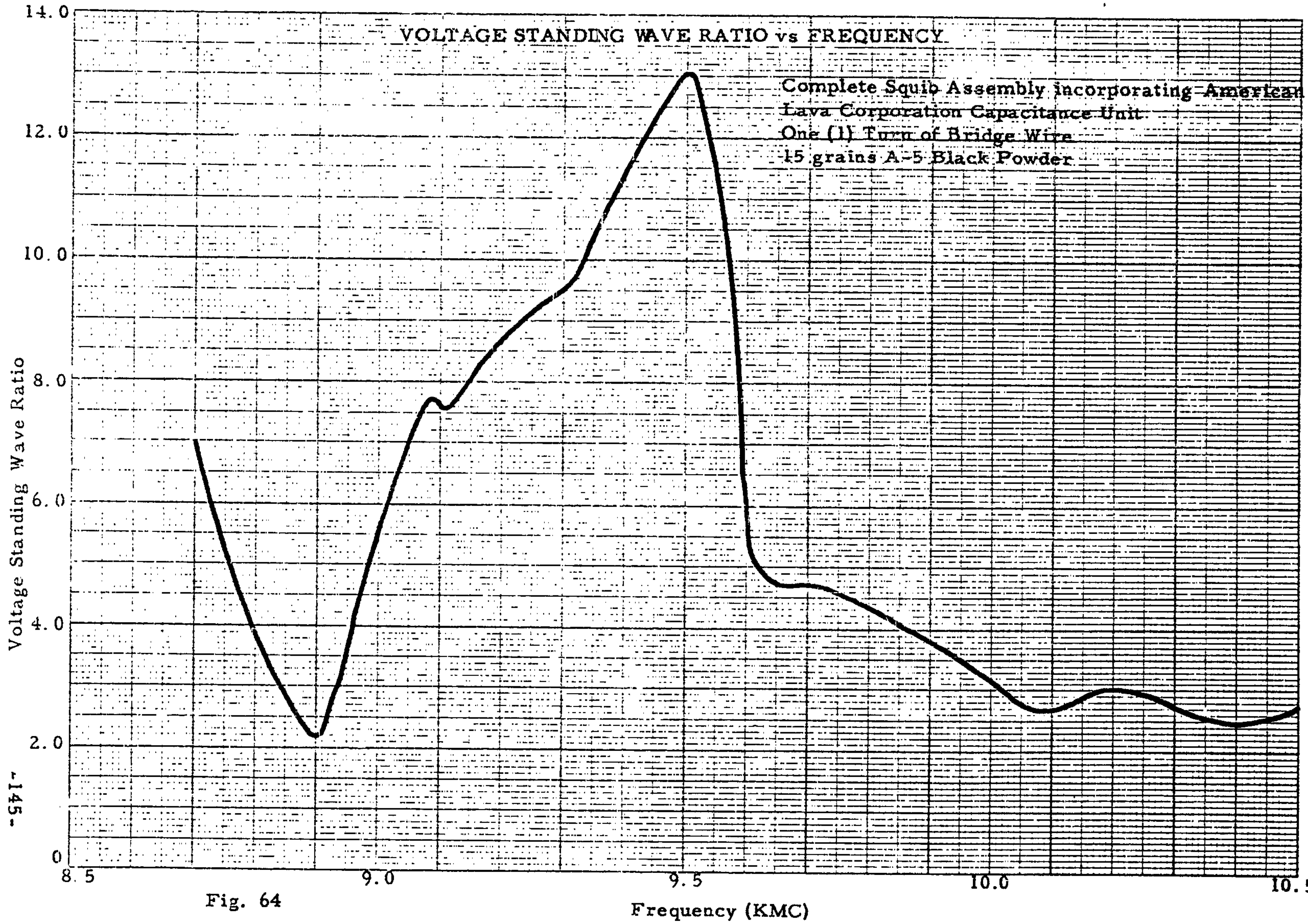
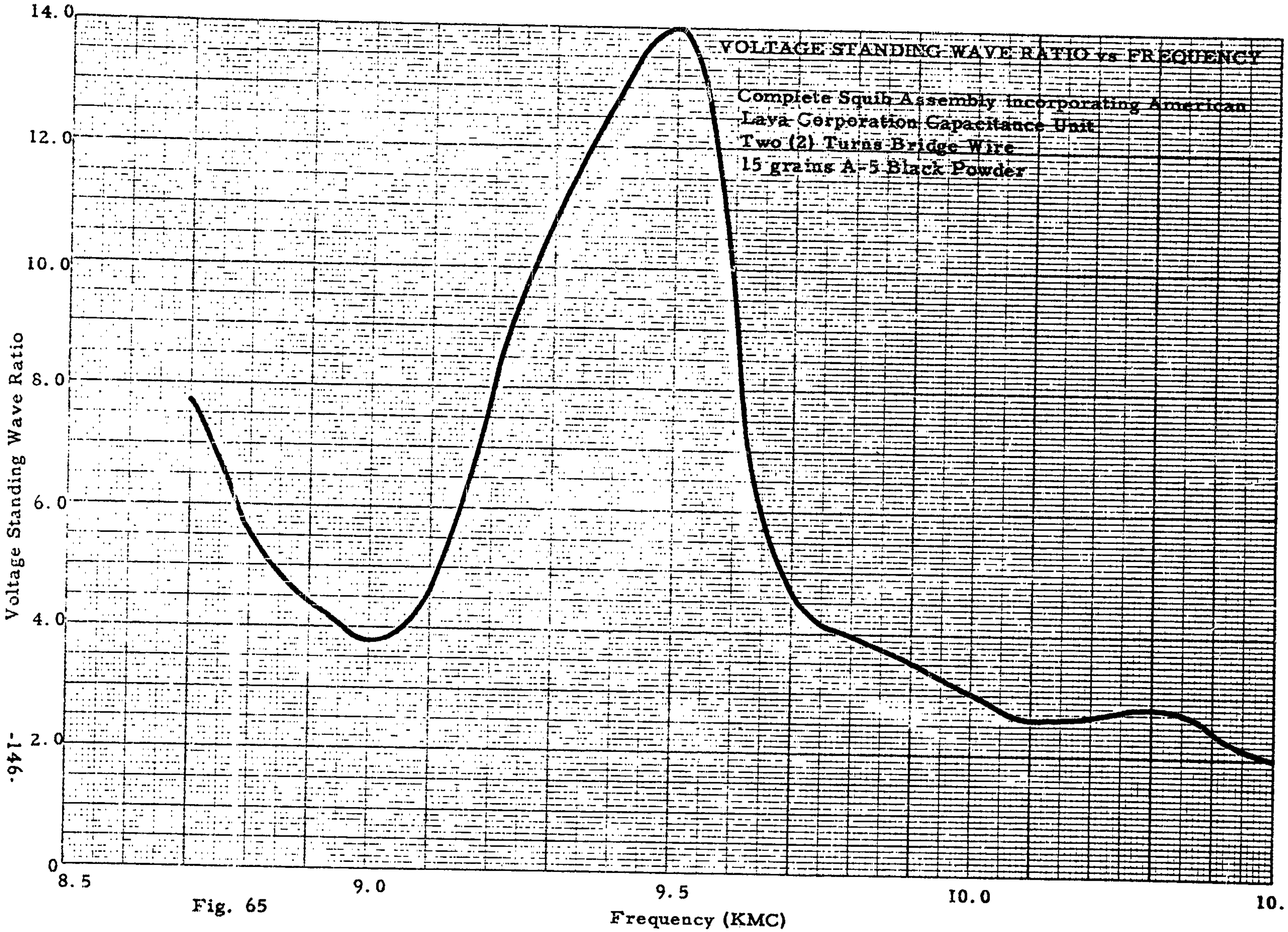

VOLTAGE STANDING WAVE RATIO vs FREQUENCY
Complete Squib Assembly incorporating American
Lava Corporation Capacitance Unit
One (1) Turn of Bridge Wire
15 grains A-5 Black Powder
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0
8.5
9.0
9.5
10.0
10.5
Voltage Standing Wave Ratio
Frequency (KMC)

Fig. 64



VOLTAGE STANDING WAVE RATIO vs FREQUENCY
Complete Squib Assembly incorporating American
Lava Corporation Capacitance Unit
Two (2) Turns Bridge Wire
15 grains A-5 Black Powder
Voltage Standing Wave Ratio
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0
8.5
9.0
9.5
10.0
10.5
Frequency (KMC)

Fig. 65

Impedance Measurements at Various Frequencies Using a Complete Squib Assembly and incorporating American Lava Corporation Capacitance Assembly, Two (2) Turns Bridge Wire and 15 grains A-5 Black Powder

$C = 0.3\ \mu f$
$R = 29.5\ \Omega$

Surge $Z_o = 50\ \Omega$

Frequency (KMC)	Point No.	$Z_L (\Omega)$
5.90	1	15.0 - j 160.0
6.00	2	6.5 - j 98.4
6.10	3	7.5 - j 51.0
6.20	4	4.5 - j 27.0
6 30	5	2.25-j 22.0
6.40	6	2.5 - j 9.5
6.50	7	2.5 - j 5.5

Table LIII

IMPEDANCE OR ADMITTANCE COORDINATES

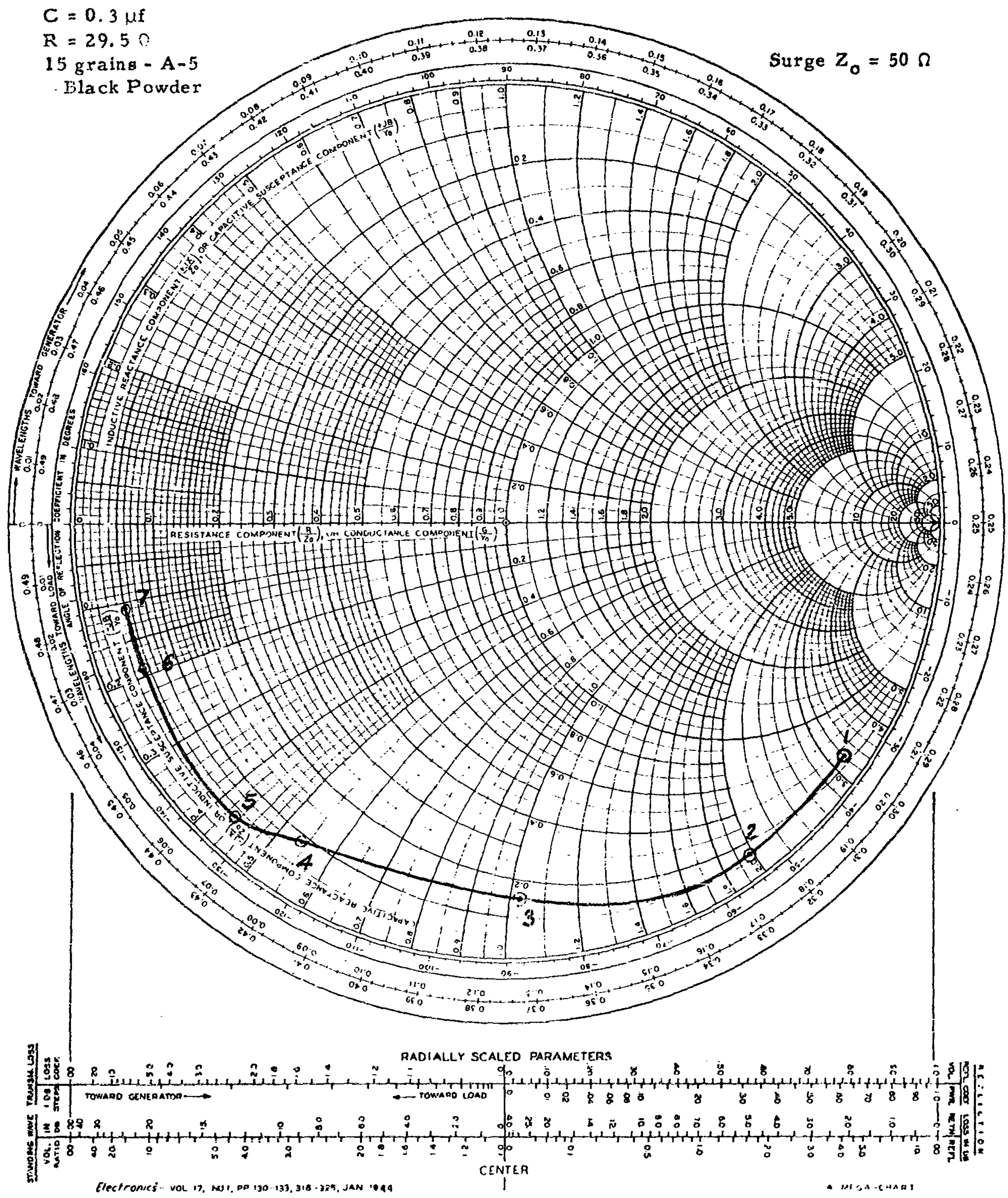


Fig. 66 - Impedance Measurements at Various Frequencies using a Complete Squib Assembly incorporating American Lava Corporation Elements.

V. SQUIB IGNITION STUDIES

Contract requirements directly and indirectly rendered necessary rather extended studies of the explosive aspects of squibs. These studies actually encompassed three distinct activities. Initially, a theoretical analysis had to be made of the transient heating of various sizes of bridge wires by step function type current pulses of diverse amplitudes. This work served such ends as providing basic, squib design data; information pertinent to bead mix specifications; and a basis for ready modification of laboratory model squibs. Secondly, the ignition properties of two grades of bead mixes potentially applicable to squibs required investigation. This inquiry, which necessarily was correlated with determinations made in the initial effort, was to provide certain practical information on squib design and performance. Finally, data for a Current-Time Ignition Characteristic, data derived from firings of a large number of squibs, had to be accumulated. Entailing this activity was a need for base or reference values of current wherewith histographic representations of current protection ratios, associated with laboratory model squibs, could be prepared. It was from this effort, incidentally, that the 30.0-second base current figure of 0.30 ampere, shown on included histograms, was obtained.

Rather complete details on the first of the aforementioned studies are contained in Appendix D, entitled "Derivation Of An Approximate Expression For The Transient Heating Of A Squib Bridge Wire When Traversed By A Constant Current." From the relationship there given for the temperature of a bridge wire as a function of the time during which a current of selected value flows through it,families of transient heating curves were plotted. Two such families of curves, one plot having applicability to a 0.002 inch diameter bridge wire and a second to a 0.0025 inch diameter wire, constitute Figs. 67 and 68 Data for the 0.002 inch diameter wire characteristic were computed from the equation

$$T = \left[\frac{3.24 I}{0.000768 - 0.000540 I}\right] \left\{ 1 - \mathcal{E}^{-\left[\frac{0.000768 - 0.000540 I}{0.00004504}\right] t} \right\} + 20 \quad (5.1)$$

while data for the 0.0025 inch diameter wire curves were found from

$$T = \left[\frac{2.07 I}{0.0006085 - 0.000345 I}\right] \left\{ 1 - \mathcal{E}^{-\left[\frac{0.0006085 - 0.000345 I}{0.0000705}\right] t} \right\} + 20 \quad (5.2)$$

Adaptation of the results of this analysis to the ends indicated earlier is rather apparent.

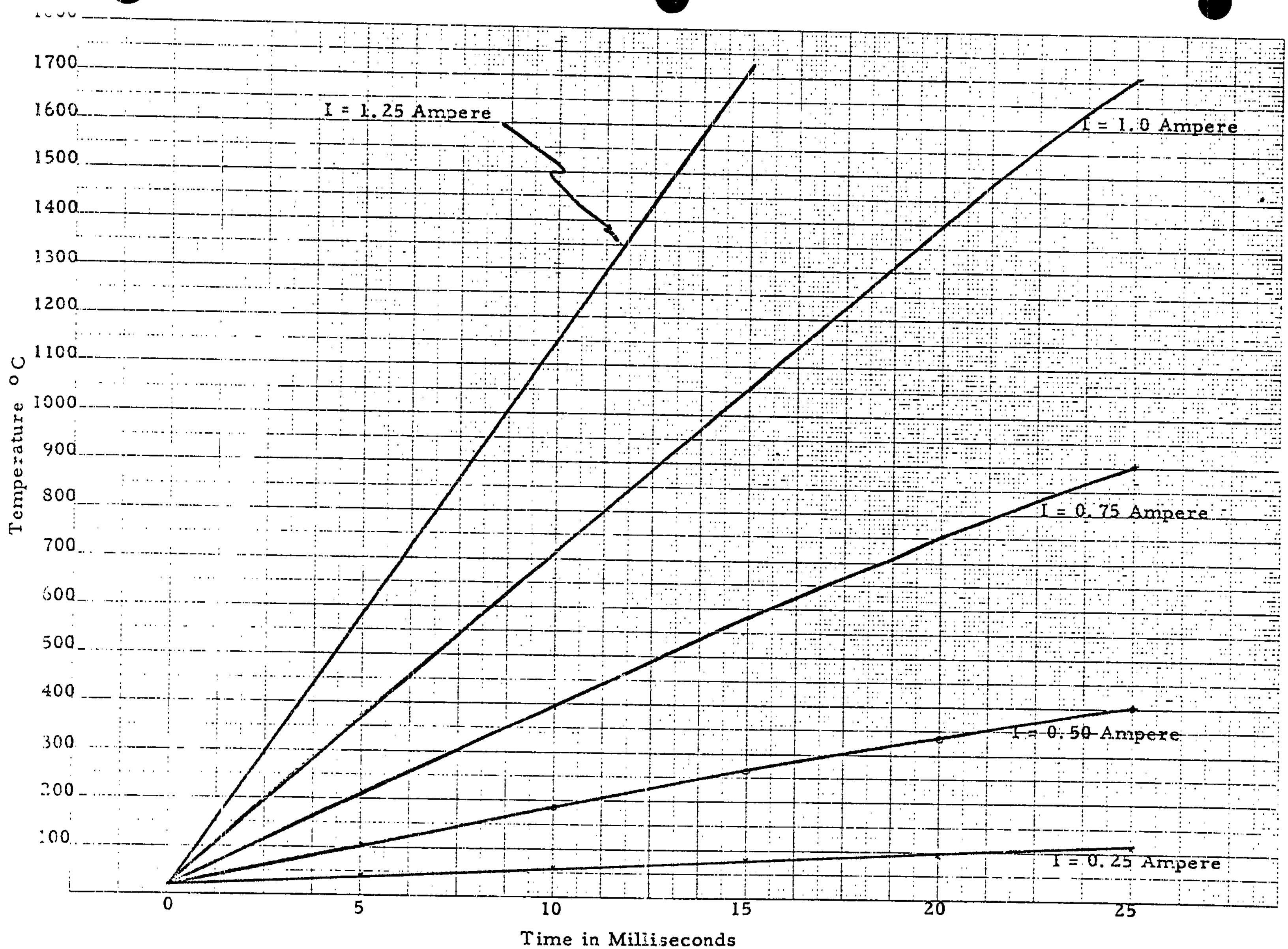


Fig. 67 - Temperature vs time, applied current held constant, for a one (1) inch length of #44, 0.002 inch diameter Ni 80%, C_r 20% Bridge Wire

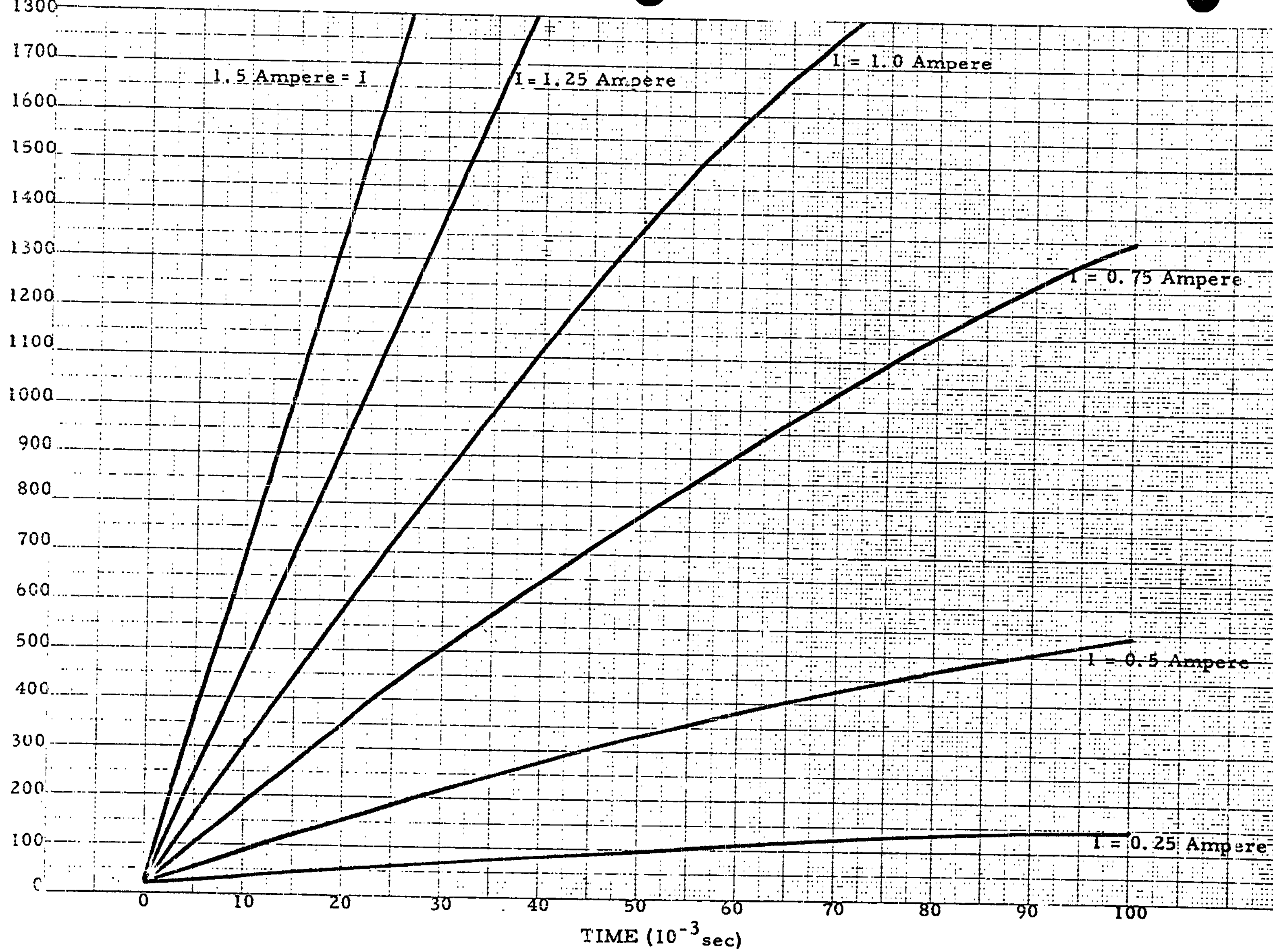


Fig. 68 - Temperature vs time, applied current held constant, for a one (1) inch length of #42, 0.0025 inch diameter Ni 80%, Cr 20% bridge wire

A somewhat ramified endeavor characterized the investigation into ignition properties of bead mixes. Giving rise to that, in large part, was the need for special data. To meet this need consultations were held with representatives of the DuPont Eastern Laboratory; design and construction were carried out on some specialized timing and switching apparatuses; and a number of out of the ordinary tests performed on the mixes. Circuit diagrams of two such apparatuses, a one shot multivibrator type pulse timer and a phantastron timer (11), are shown in Fig. 69. Serving to illustrate the manner in which these apparatuses were employed is the block diagram of Fig. 70. Bead mix tests, most of which were singularly objective, providing essential squib design data, consisted in the forcing of 10 0-millisecond current pulses through given sized bridge wires on which bead mixes had been deposited, and noting, after a succession of increases in the current magnitude, that value of current which effected consistently bead mix ignitions. Much of the described sequence may be discerned from examination of the entries in Tables LIV and LV, these indicating the performance of two grades of mix.

Bead mixes subjected to test were of two kinds, and were compounded newly for each extended phase of this study by personnel of the DuPont Eastern Laboratory. One of the mixes, designated DuPont No. 4, was a recently developed product of an undisclosed composition, this not admitting of divulgence; the second of the mixes was conventional lead styphnate (25) (27). Outwardly, the DuPont No. 4 mix appeared as a brown paste whose elements tended to separate at room temperatures. Approximate ignition temperature properties were revealed to be: (a) Instantaneous ignition = 490° C; (b) 60-second spontaneous ignition = 236° C. Corresponding ignition temperature properties of the lead styphnate were as follows: (a) Instantaneous Ignition = 320° C; (b) 5-second ignition = 282° C; (c) 10-second ignition = 276° C; (d) 15-second ignition = 272° C; (e) 20-second ignition = 267° C. Additionally, the No. 4 bead mix has a functioning time of 4.5 milliseconds whereas that of lead styphnate amounts to about 0.30 millisecond. Some undetermined thermal differences, presumably in the thermal conductivity and capacity, must exist about the two mixes as performances thereof on bridge wires are practically the same.

Set forth in Fig. 71 is the Current-Time Ignition Characteristic used for base or reference purposes in this project. It was obtained, as may be seen by examination of Tables LVI and LVII, by firing at selected time intervals a minimum of three squib samples, and noting the respective values of current which caused detonations. Plotting difficulties, incidentally, rendered inadvisable representations of all the points, only about 20% being shown. Since variations existed among the squibs a spread in current values appeared. This led to containment of the points between two bounding curves and to delineation through the aggregate of points of a mean or average characteristic. From this last were taken such data as were required for calculation of degrees of protection that were afforded

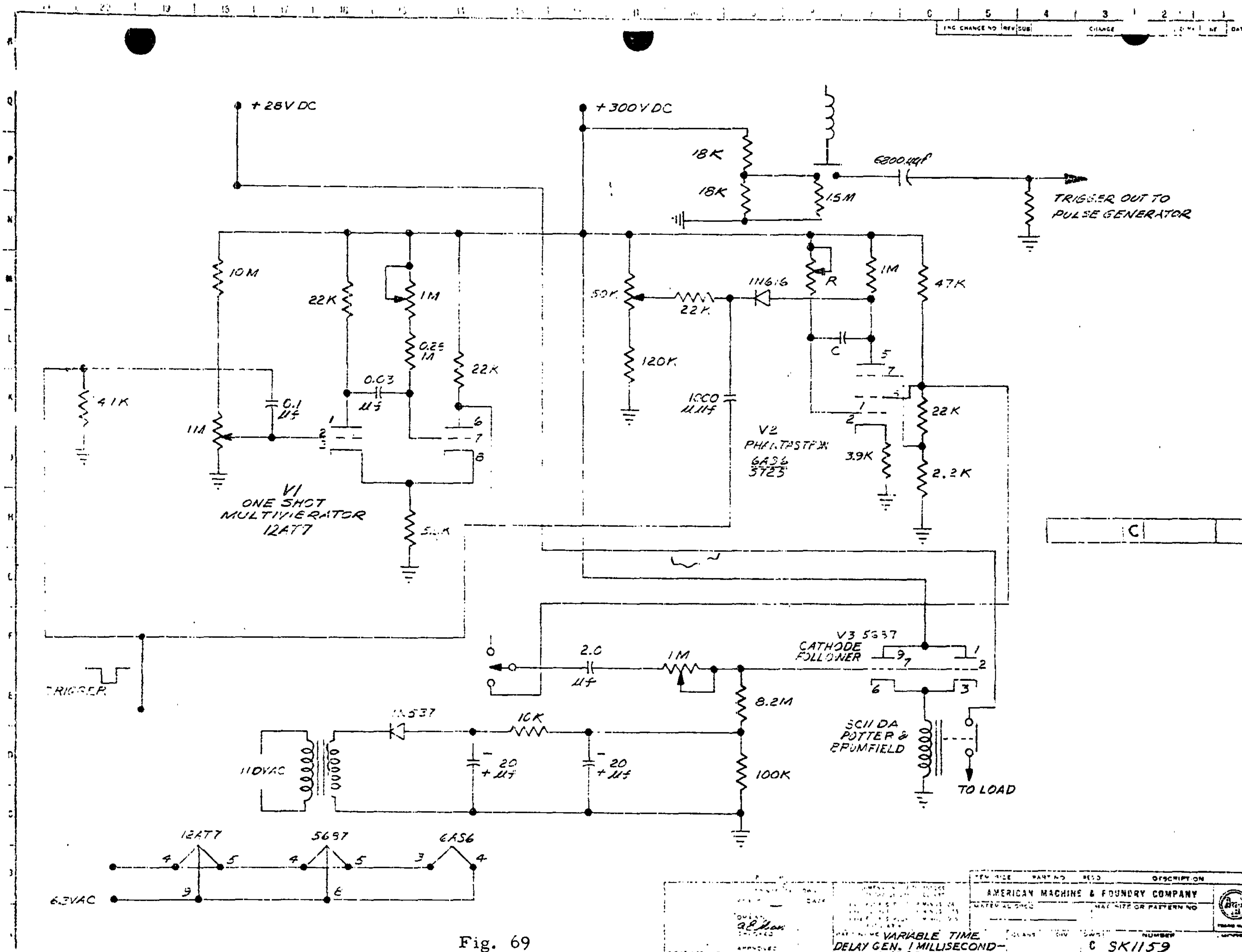
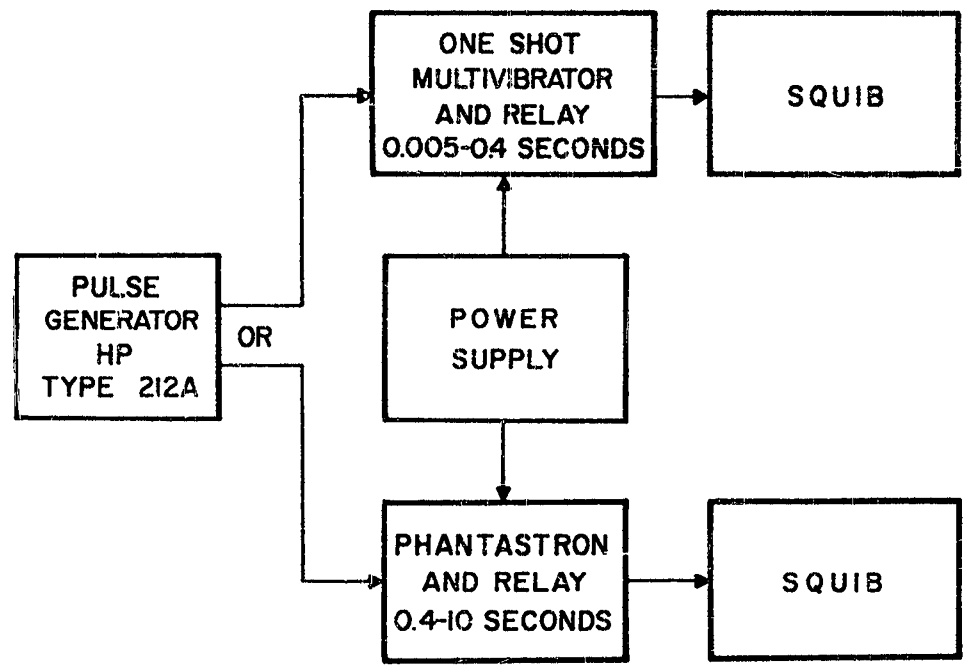

+28V DC
+300V DC
18K
18K
1.5M
6800μμf
TRIGGER OUT TO
PULSE GENERATOR
10M
22K
1M
0.25 M
22K
0.03 μf
0.1 μf
4.1K
1M
V1
ONE SHOT
MULTIVIBRATOR
12AT7
50K
120K
22K
1N616
R
1M
47K
C
1000 μμf
V2
6AS6
5725
3.9K
22K
2.2K
TRIGGER
2.0 μf
1M
V3 5687
CATHODE
FOLLOWER
8.2M
100K
SC11DA
POTTER &
BRUMFIELD
TO LOAD
110VAC
10K
20 μf
20 μf
12AT7
5687
6AS6
6.3VAC
AMERICAN MACHINE & FOUNDRY COMPANY
VARIABLE TIME
DELAY GEN. 1 MILLISECOND–
10 SECONDS
C SK1159

Fig. 69



CURRENT, TIME SQUIB IGNITION BLOCK DIAGRAM.

FIGURE 70

PERFORMANCE OF DUPONT NO. 4 BEAD MIX

Time Duration of Current Flow = 10^{-2} seconds

Sample No.	Current (Amperes) 0.75	1.00	1.25	1.50	1.75
1–5	Unaffected	Ignition of all beads on 0.00175" diameter bridge wire			
6–15	Unaffected	Unaffected	Ignition on all beads on 0.002" diameter bridge wire		
16–25	Unaffected	Unaffected	Unaffected	Unaffected	Ignition on all beads on 0.0025" diameter bridge wire

Table LIV

PERFORMANCE OF DUPONT LEAD STYPHNATE BEAD MIX

Time Duration of Current Flow = 10^{-2} seconds

Sample No.	Current (Amperes) 0.50	0.75	1.00	1.25	1.50	1.75
1, 2, 3, 4, 5, 6	Unaffected	Ignition of all beads on 0.00175" diameter bridge wire				
7, 8, 9, 10, 11, 12	Unaffected	Unaffected	Unaffected	Ignition of all beads on 0.002" diameter bridge wire		
13, 14, 15, 16, 17, 18	Unaffected	Unaffected	Unaffected	Unaffected	Unaffected	Ignition of all beads on 0.0025" diameter bridge wire

Table LV

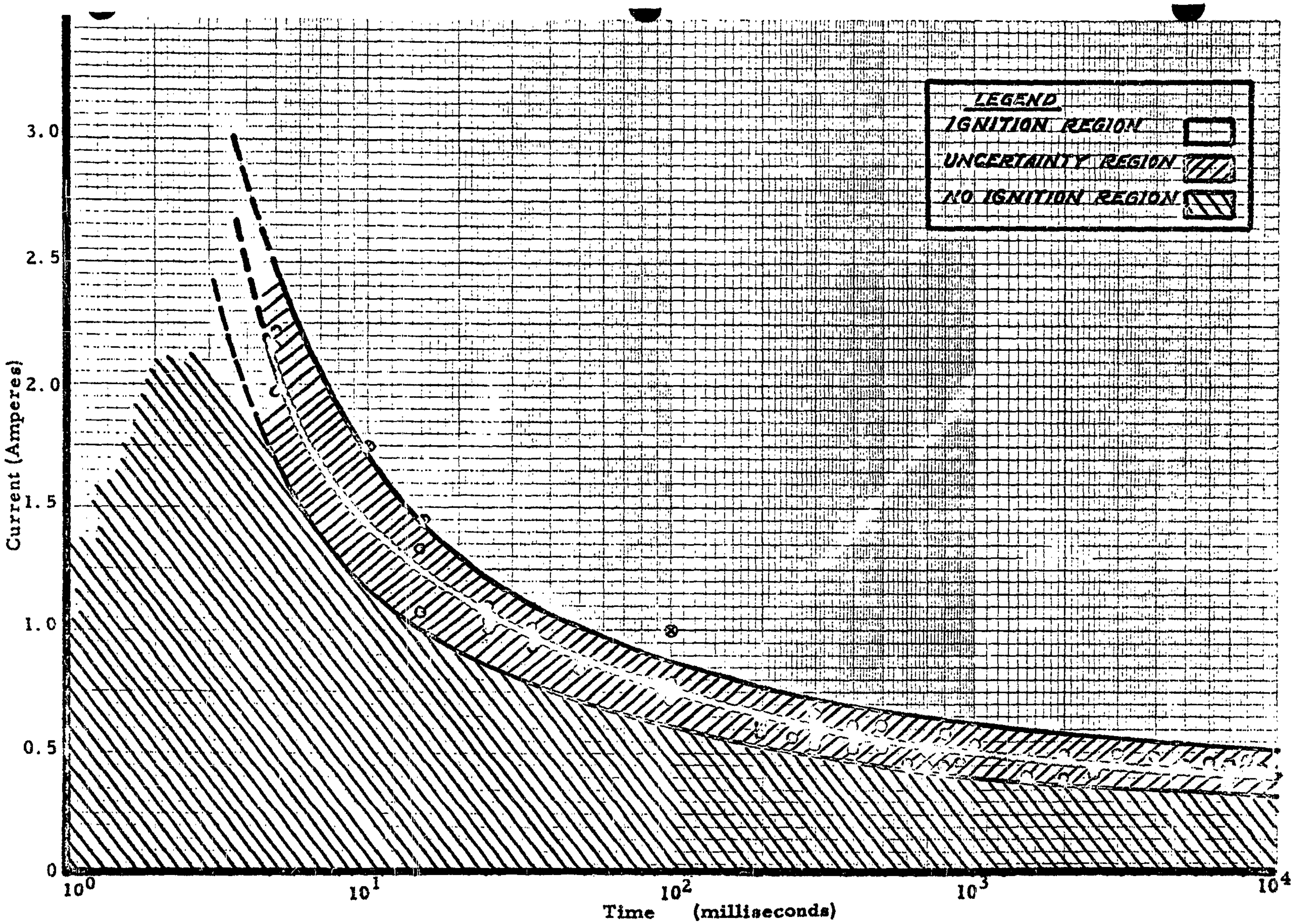


Fig. 71 - Current-Time Ignition Characteristic for Squib
Squib is comprised of: 0.002" Nichrome Tophet "A" Resistance Wire, Lead Styphnate Bead Mix and A-5 Black Explosive Powder (15 grains)

Current-Time Ignition Characteristics for Squib

Squib is comprised of: 0. 002" Nichrome Tophet "A" Resistance Wire, Lead Styphnate Bead Mix and A-5 Black Explosive Powder (15 grains)

Time Duration of Current in Milliseconds

Sample No.	Time (10^{-3} sec.)	Current (amperes)
1	5. 0	2. 15
2	5. 0	2. 22
3	5. 0	1. 97
4	10. 0	1. 43
5	15. 0	1. 07
6	15. 0	1. 34
7	15. 0	1. 42
8	25. 0	1. 04
9	25. 0	1. 01
10	25. 0	1. 10
11	35. 0	1. 01
12	35. 0	0. 98
13	35. 0	0. 94
14	50. 0	0. 87
15	50. 0	0. 89
16	50. 0	0. 84
17	100. 0	0. 78
18	100. 0	0. 72
19	100. 0	0. 74
20	150. 0	0. 68
21	150. 0	0. 69
22	150. 0	0. 70
23	200. 0	0. 62
24	200. 0	0. 64
25	200. 0	0. 58
26	250. 0	0. 57
27	250. 0	0. 57
28	250. 0	0. 61
29	300. 0	0. 67
30	300. 0	0. 53
31	300. 0	0. 57
32	400. 0	0. 61
33	400. 0	0. 52
34	500. 0	0. 53
35	500. 0	0. 56
36	500. 0	0. 62
37	600. 0	0. 45
38	600. 0	0. 45
39	600. 0	0. 53
40	700. 0	0. 44
41	700. 0	0. 50
42	700. 0	0. 50

Table LVI

Current-Time, Ignition Characteristics for Squib (Continued)

Sample No.	Time (10^{-3} sec.)	Current (amperes)
43	800.0	0.45
44	800.0	0.51
45	800.0	0.58
46	900.0	0.47
47	900.0	0.47
48	900.0	0.51
49	1,000.0	0.52
50	1,000.0	0.54
51	1,000.0	0.53
52	1,500.0	0.40
53	1,500.0	0.48
54	1,500.0	0.48
55	2,000.0	0.40
56	2,000.0	0.47
57	2,000.0	0.50
58	2,500.0	0.43
59	2,500.0	0.44
60	2,500.0	0.45
61	3,000.0	0.45
62	3,000.0	0.43
63	3,000.0	0.50
64	4,000.0	0.42
65	4,000.0	0.48
66	5,000.0	0.45
67	5,000.0	0.46
68	6,000.0	0.40
69	6,000.0	0.40
70	6,000.0	0.46
71	7,000.0	0.40
72	7,000.0	0.38
73	7,000.0	0.47
74	8,000.0	0.42
75	8,000.0	0.46
76	8,000.0	0.47
77	9,000.0	0.39
78	9,000.0	0.43
79	9,000.0	0.43
80	10,000.0	0.40
81	10,000.0	0.42
82	10,000.0	0.42

Table LVI

Current-Time Ignition Characteristics for Squib

Squib is comprised of: 0.002" Nichrome Tophet 'A' Resistance Wire, Lead Styphnate Bead Mix and A-5 Black Explosive Powder (15 grains)

Time Duration of Current in milliseconds

Sample No.	Time (10^{-3} sec.)	Current (Amperes)
1	10	1.75
2	10	1.50
3	10	1.50
4	25	1.00
5	25	1.00
6	25	1.00
7	100	1.00
8	100	0.75
9	100	0.75
10	1,000	0.75
11	1,000	0.50
12	1,000	0.50
13	2,500	0.50
14	2,500	0.50
15	2,500	0.50
16	6,000	0.50
17	6,000	0.50
18	6,000	0.50
19	10,000	0.50
20	10,000	0.50
21	10,000	0.50

Table LVII

squibs by reactive units. Essential facts about the elements comprising the squib are given in the headings of Tables LVI and LVII. To this it may be well to add that the squib size, configuration, parts arrangements, etc. were made as nearly like those of the laboratory model squib as practicable.

VI. DELAY TIME EFFECTS

In the course of this program an investigation was made to determine the effect of the shunting reactance insofar as delay time is concerned in the intentional firing circuit. This problem was attacked by mathematical analysis. Specifically, a solution was obtained for the composite current, steady-state and transient, that would be caused to flow in a laboratory model squib energized from a conventional twenty-four-volt source over a transmission line one hundred feet long. The details of this mathematical analysis are presented in Appendix E to this report. The results obtained in this analysis are in agreement with oscillatory-case measurements made by Mr. R. F. Wood of The Franklin Institute.

Since the results of this analysis indicate a delay time of the order of a few microseconds, it is concluded that the effect is negligible.

VII. WIDE BAND RADIO FREQUENCY ABSORBERS

While the primary emphasis in this program was placed on the use of reactive elements in shunt with the bridge wire, consideration was also given to the use of wide band radio frequency absorbers as a supplementary technique. To this end samples of wide band radio frequency absorbers were obtained from The Franklin Institute in Philadelphia, Pa. Specifically, nine sample absorbers were obtained - three of the larger size and six of the smaller size - as depicted in Photo 11. Also furnished by The Franklin Institute was a typical attenuation characteristic for the broad band absorber shown in Figure 72. In this characteristic the dotted portion is an extrapolation from the measured portion of the curve.

With regard to the larger size absorbers (Photo 11) no data is furnished in this report. In the course of initial impedance measurements all three samples suffered voltage breakdown. The time schedule of the current phase of the program did not permit obtaining replacement samples and conducting tests on this particular configuration of the broad band radio frequency absorber.

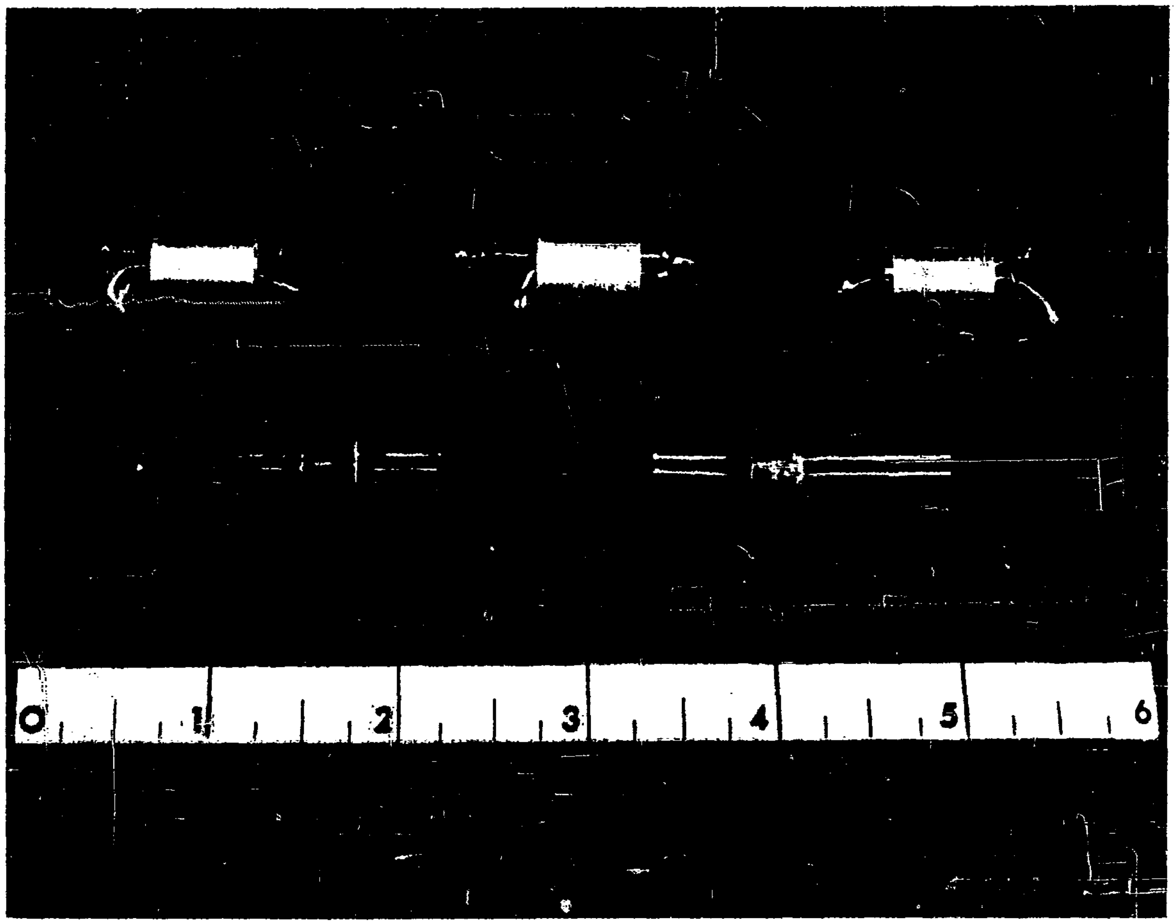
With regard to the smaller size of broad band radio frequency absorber (Photo 11) a number of tests were performed. Impedance measurements were made at various frequencies from 50 megacycles to 1000 megacycles and the data are recorded in Table LVIII. The Smith Chart presentation of the impedance over the 50 mc to 1000 mc range is given in Figure 73.

Figure 74 is a plot of current protection ratio versus frequency for a squib using a cluster of three cylindrical titanate capacitance units, obtained from the American Lava Corporation, in conjunction with a type MDP-1 absorber. Figure 75 is a plot of the current protection ratio versus frequency for a squib using a cluster of three cylindrical capacitance units, supplied by the Erie Resistor Company, in conjunction with a type MDP-1 absorber.

Figure 76 shows plots of current protection ratio vs. frequency for a squib using a cluster of three cylindrical capacitance units, supplied by American Lava Corporation, in conjunction with three different samples of broad band radio frequency absorbers.

Figure 77 shows plots of current protection ratio vs. frequency for a squib utilizing a cluster of three cylindrical capacitance units, supplied by the Erie Resistor Corporation, in conjunction with two separate samples of broad band radio frequency absorbers.

From these data it appears that the broad band radio frequency absorber contributes little or nothing to the protection ratio at frequencies below approximately 500 megacycles. However, at frequencies above approximately 500 megacycles the current protection ratio achieved is primarily attributable to the broad band absorber.



Photograph 11. View of typical Franklin Institute Radio-Frequency energy absorbers.

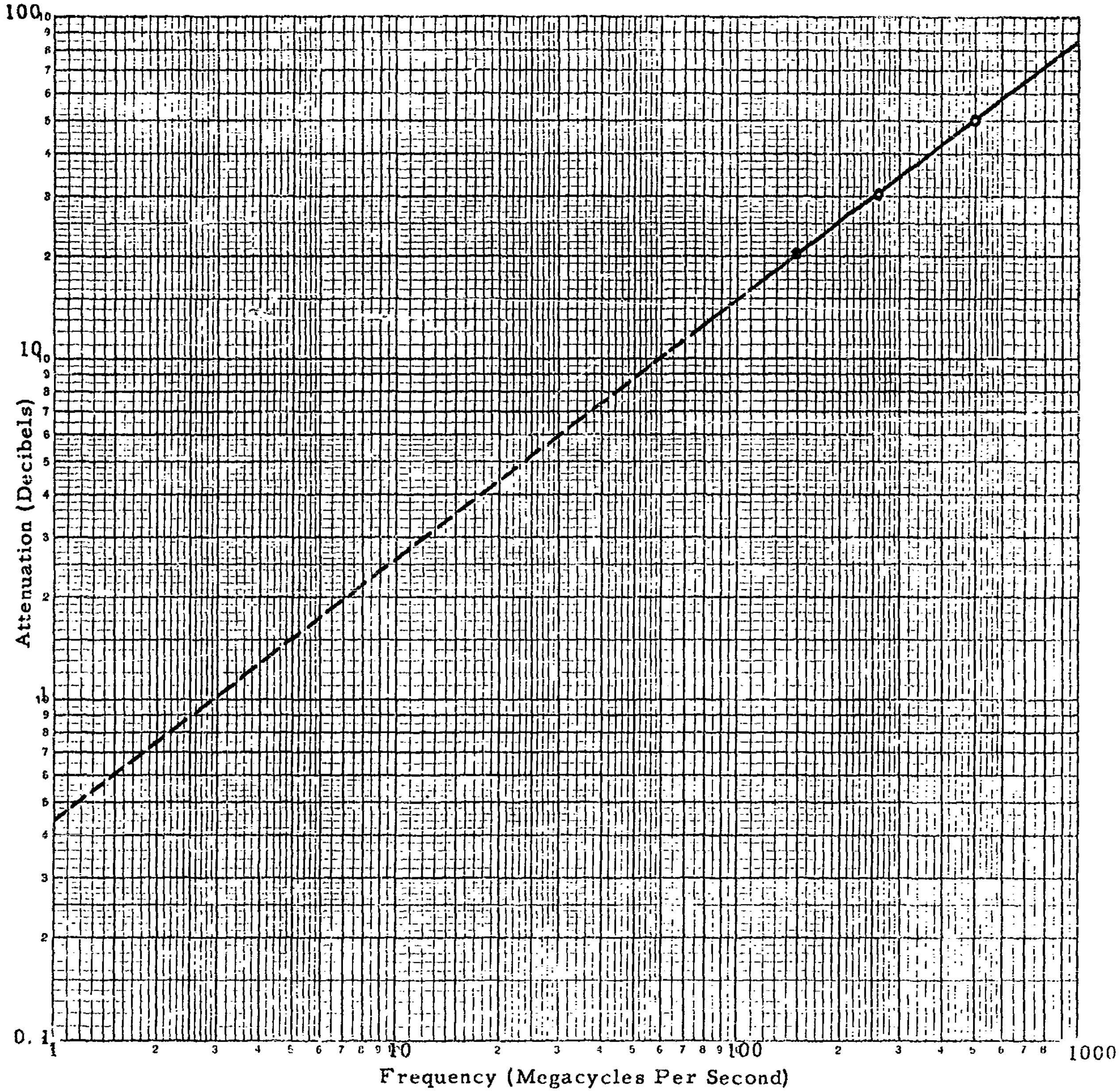


Fig. 72 - Attenuation Characteristic of Twin-Lead, Broadband, Radio-Frequency Energy Absorbers Furnished By the Franklin Institute On 12 June 1961

Impedance Measurements At Various Frequencies Using Absorber #4038

Surge $Z_o = 50\ \Omega$

Frequency (mc)	Point No.	Z_R (Ω)
50	1	7.4 - j 23.50
100	2	16.5 + j 6.75
150	3	30.0 + j 18.50
200	4	43.8 + j 4.00
250	5	34.2 - j 3.75
300	6	28.0 - j 1.25
400	7	27.2 + j 6.25
500	8	27.5 + j 9.75
600	9	28.8 + j 15.25
700	10	31.3 + j 17.80
800	11	33.5 + j 20.00
900	12	36.8 + j 25.00
1000	13	40.0 + j 30.30

Table LVIII

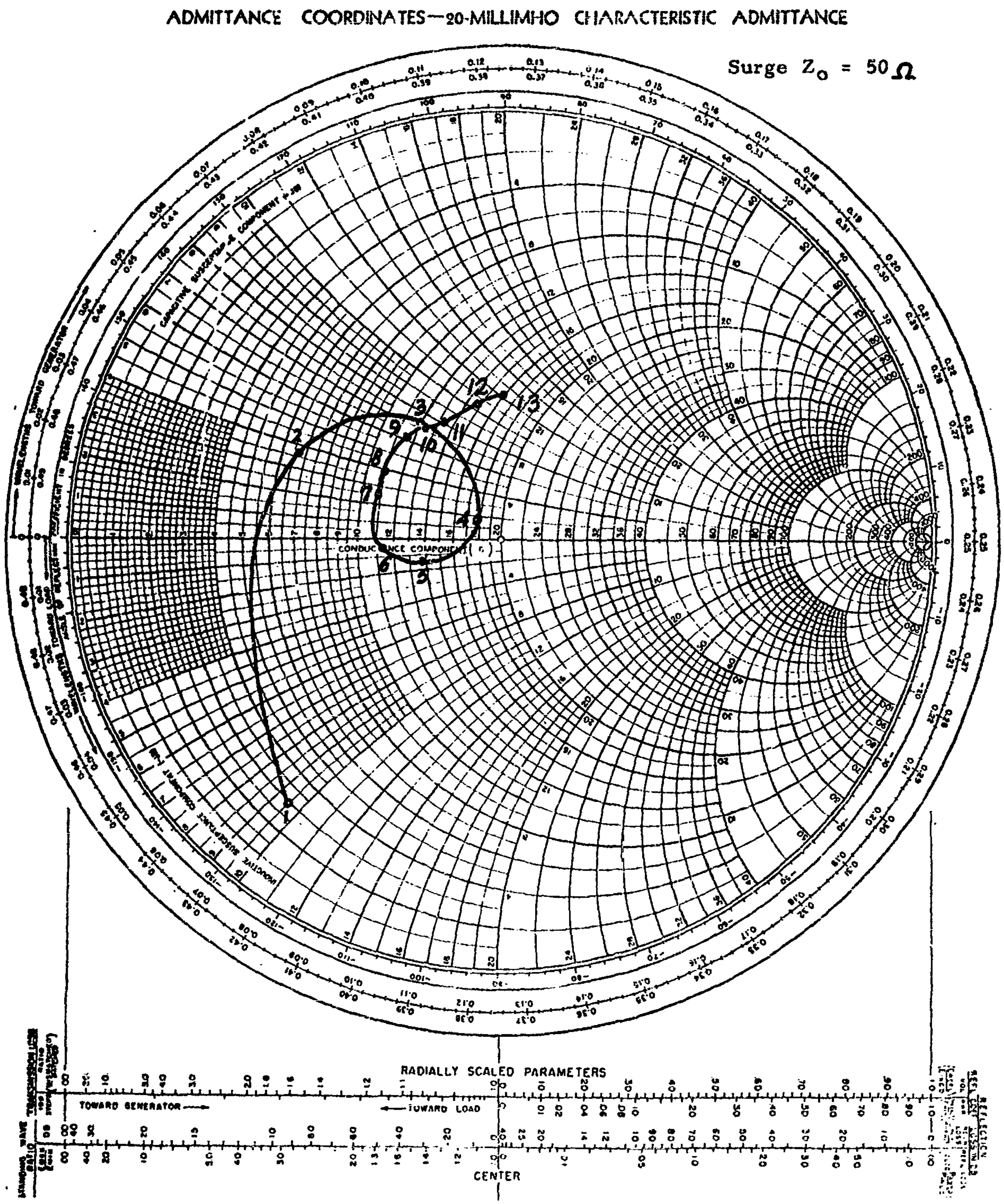


Fig. 73- Impedance Measurements at Various Frequencies Using Absorber #4038

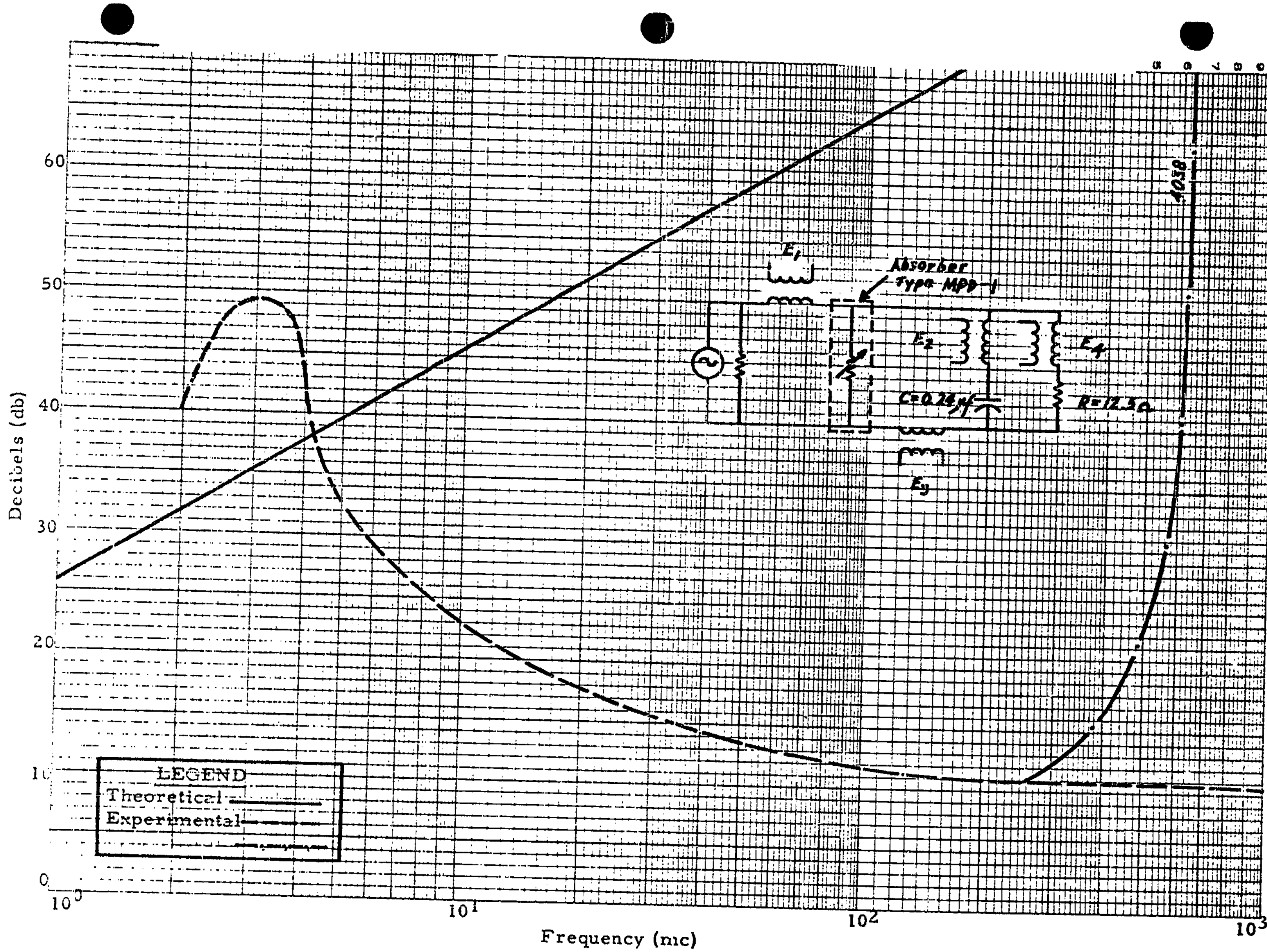


Fig. 74 Current Protection Ratio Characteristics (Cluster of three (3) Cylindrical Titanate Units) Sample #7 from lot submitted by American Lava Corporation on 6 March 1961; 0.002" Resistance Wire; and Type MDP-1 Absorber

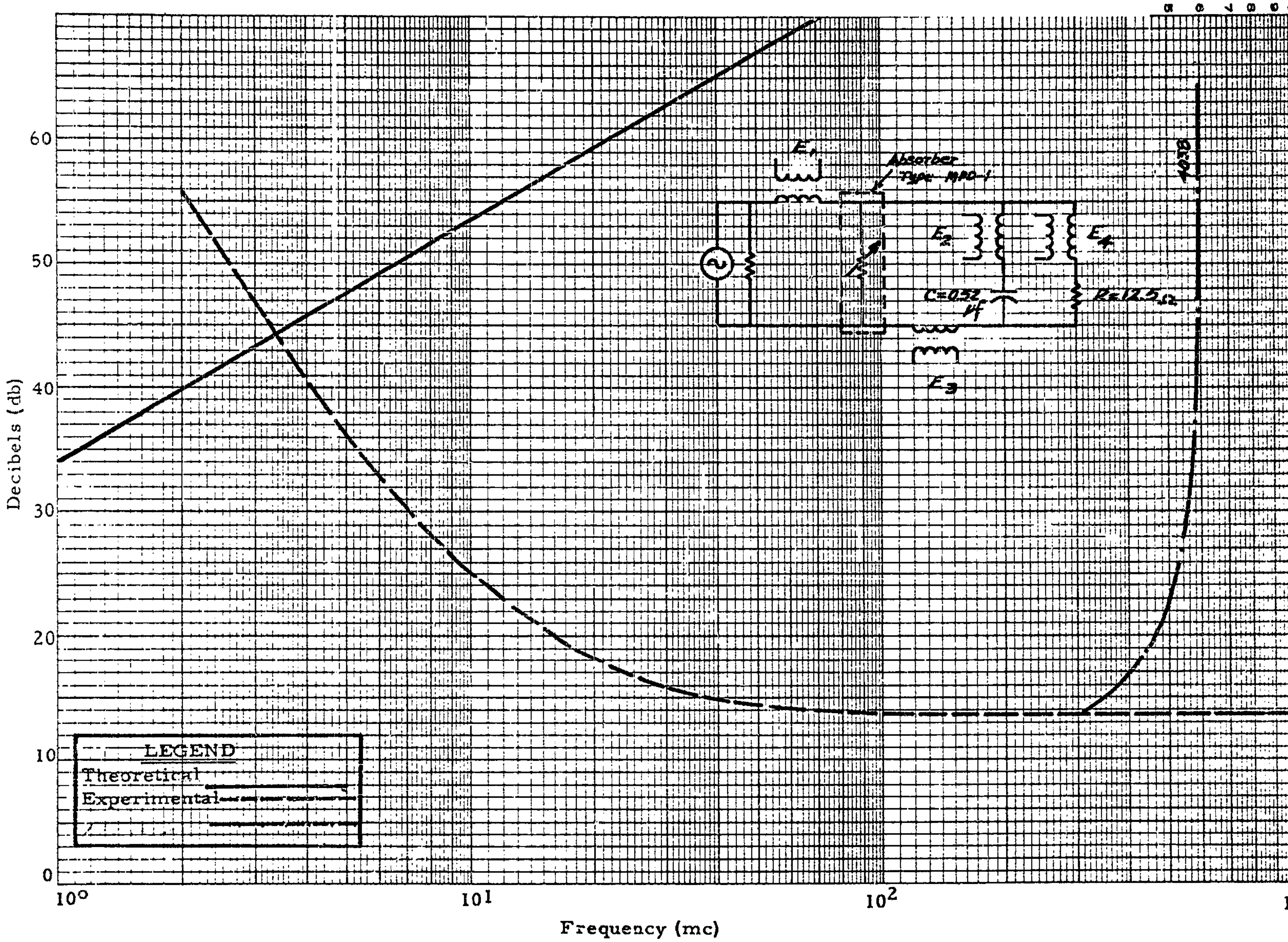


Fig. 75 - Current Protection Ratio Characteristics (Cluster of three (3) Cylindrical Capacitance Units)
Sample #2 from lot submitted by Erie Resistor Corporation on 10 January 1961;
0.002" Resistance Wire; and Type MPD-1 Absorber

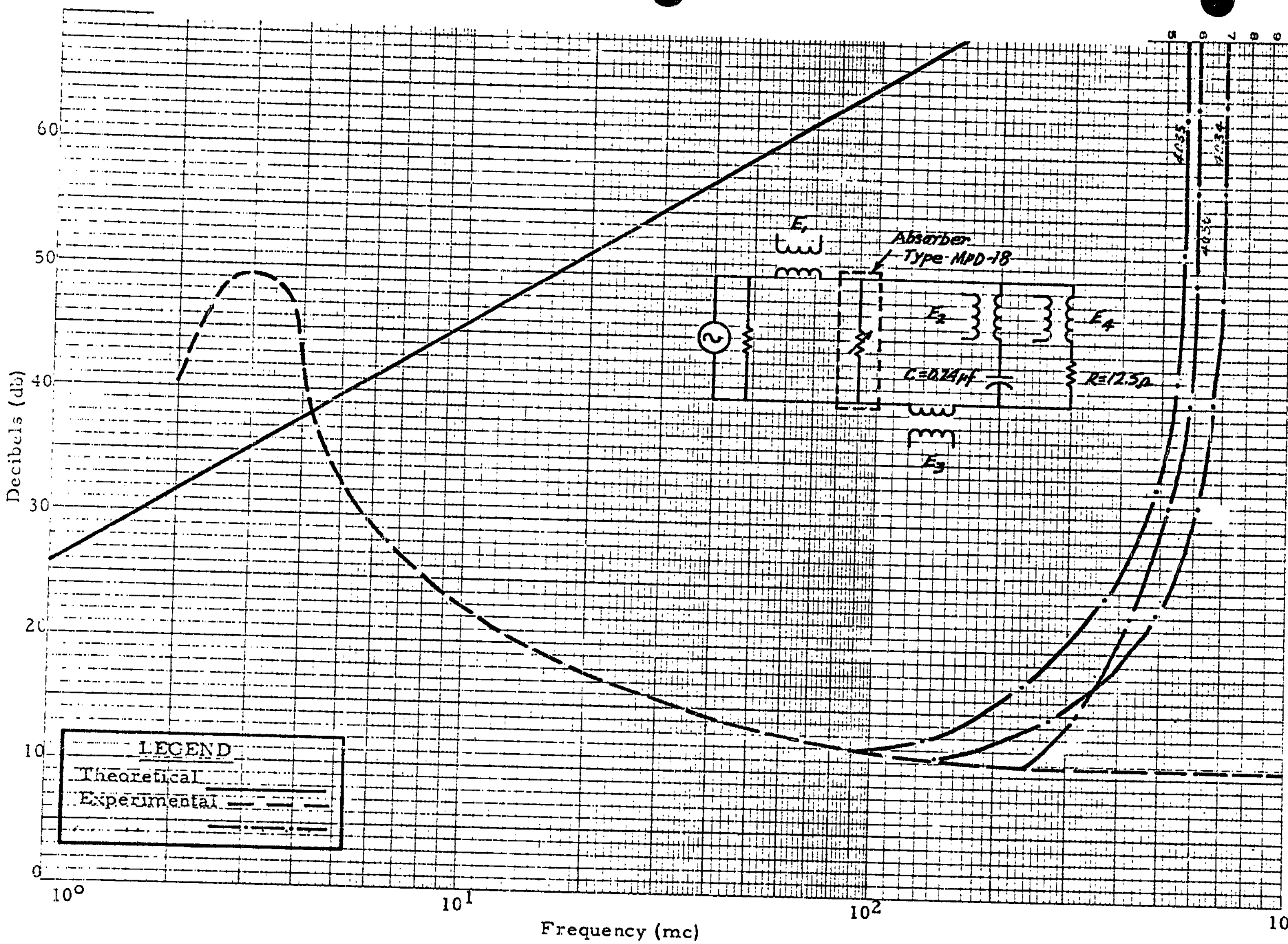


Fig. 76 - Current Protection Ratio Characteristics (Cluster of Three (3) Cylindrical Titanate Units) Sample #7 from lot submitted by American Lava Corporation on 6 March 1961; 0.002" Resistance Wire; and Type MPD-18 Absorber

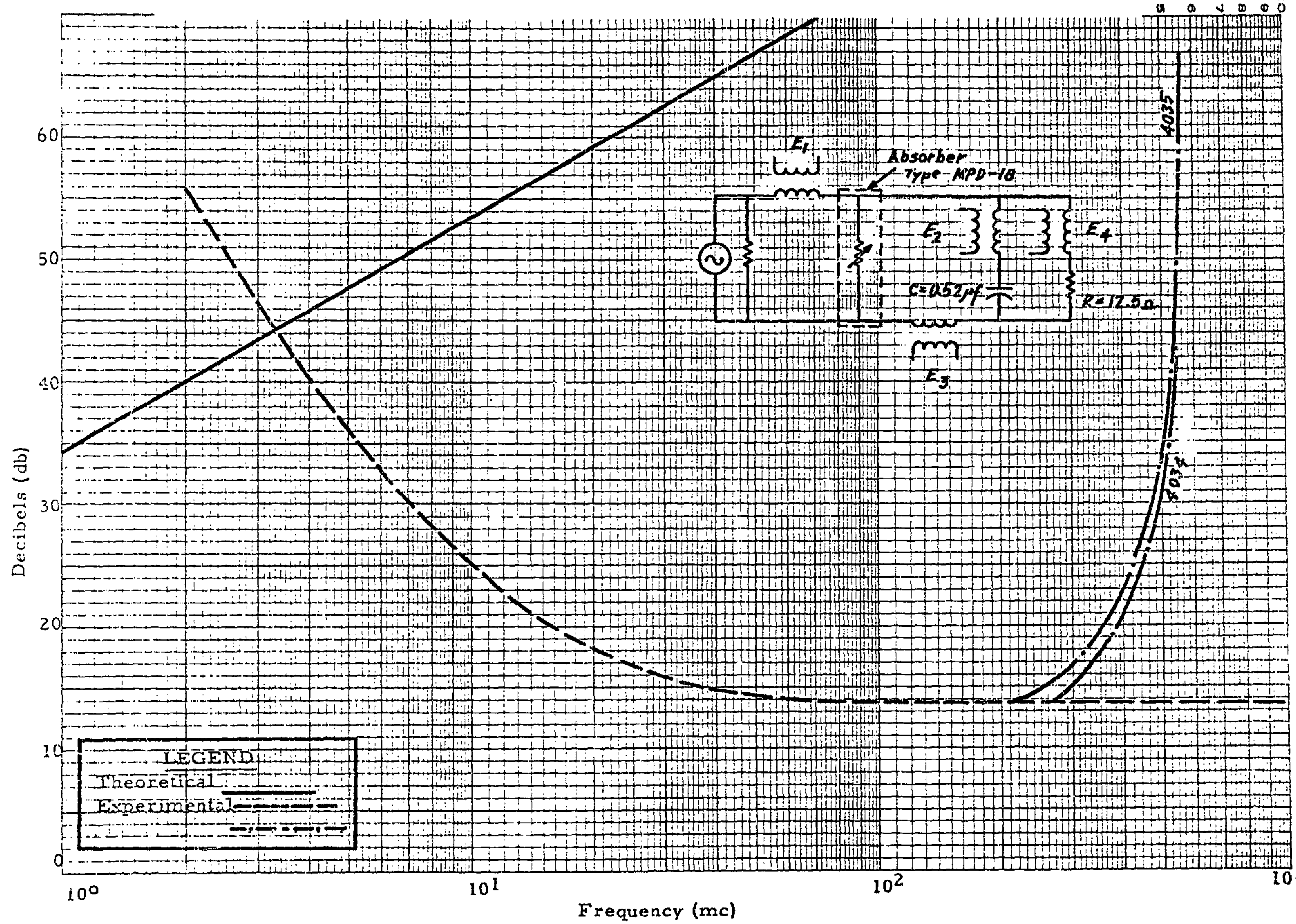


Fig. 77 Current Protection Ratio Characteristics (Cluster of three (3) Cylindrical Titanate Units)
Sample #2 from lot submitted by Erie Resistor Corporation on 10 January 1961;
0.002" Resistance Wire; and type MPD-18 absorber

VIII. FINDINGS

A. Reactance Units

One class of ceramic capacitance units investigated was characterized by very high dielectric constant (specific inductive capacity of the order of 100, 000); by high dissipation factor; and by low voltage rating. Experience in this program indicates that this class of units has not yet reached the state of development where it may be applied to squib protection. Advantages of the high dielectric constant are outweighed by shortcomings in other characteristics and in dynamic behavior. The most serious shortcoming of these units is their inability to sustain voltages of any consequence. Only on one occasion was an attempt made to obtain Current Protection Ratio characteristics with these units and then the radio frequency signals had to be held to values of the order of 1. 0 volt (RMS) to prevent behavior changes and heating of units. Detracting further from this class of capacitors is a lack of uniformity among units of the same lot. The following examples of lack of uniformity are cited:

1. In one lot of nominal 0. 45 mfd capacitor samples the dissipation factor varied from 0. 27 to 0. 49.

2. In the same lot the shunt or D-C resistance as measured in one direction ranged from 340 ohms to 4650 ohms while in the reverse direction it extended from 330 ohms to 5700 ohms. Also, when subjected to a D-C potential difference of 15. 0 volts units of this lot seemed to suffer dielectric breakdown accompanied by a large rise in current and rapid heating.

3. In another similar lot the supplier indicated that the units exhibited significant capacity decline when stressed by voltages in excess of 10. 0 volts.

In marked contrast to the first class of capacitance units is the second class or barium titanate class. Units belonging to this group, generally have demonstrated those qualities which recommend them for squib protection service. Except for some minor aging effects which certain of the units displayed, most of the electrical characteristics were quite stable. Lot uniformity, too, as may be seen from Table XVII, leaves little to be desired. On the point of voltage, again, units of this category are capable of withstanding moderately high stresses without undergoing any perceptible changes. Capacitor samples used were rated at 60. 0 volts or more and performed conventionally within the set ratings. In this class of capacitance units good performance was obtained from samples fabricated by

an extrusion process and from samples fabricated by thin film techniques. The samples fabricated by extrusion process were submitted by the American Lava Corporation and the samples fabricated by thin film techniques were submitted by the Erie Resistor Corporation.

B. Simulated Squib Test Set-Ups

1. Selected capacitance units were evaluated in simulated squib test set-ups using a bridge wire of approximately one inch length and with a D.C. resistance of the order of 10 to 15 ohms. These tests included evaluation over the continuous frequency range from 400 cps to 1000 mcps and spot checks in the microwave region at L Band, C Band, and X Band. Typical Current Protection Ratio characteristics obtained with three different capacitance unit samples are presented in Figs. 25, 26 and 27. The main differences in performance occur in the frequency range below 10 mcps. The capacitor employed in the case of Fig. 27 was clearly the better of the trio. It is noted that the protection indicated in the range 0.5 mcps to 10 mcps attains values of several hundredfold. The maxima of these characteristics ordinarily occur between 1.0 and 6.0 mcps, and efforts to shift them to higher frequencies have not met with success thus far. Typical decibel-expressed current and power protection ratios obtainable with a single device are as follows:

   a. Below 200 KC - protection is less than 15 db to zero.

   b. From 200 KC to 50 mc - protection varies in the general range from 15 db to 50 db.

   c. From 50 mc to 1000 mc - protection varies in the range from 10 db to 17 db.

   d. From 1000 mc to 11 KMC - nominally 15 db with a few very narrow frequency bands where the ratio drops to values below 10 db.

2. Tests with simulated squib set-ups were conducted utilizing a bridge wire approximately 4 inches in length and with a DC resistance of the order of 50-60 ohms. In these tests three inches of the bridge wire was coiled into turns to increase its impedance. A Current Protection Ratio characteristic illustrating the effect is presented in Fig. 18. By comparison of Fig. 18 with Figs. 25, 26, 27, it is apparent that this technique results in a substantial gain in current protection ratio at frequencies below 100 mcps. Employment of this technique, however, would require use, in the intentional firing circuit, of a DC supply of approximately 60 volts in order to assure reliable intentional firing.

3. The evaluation of wide band radio-frequency absorbing devices furnished by The Franklin Institute is given in Section VII of this report. From Figs. 74 thru 77 in Section VII it is apparent that the sample devices tested do not offer protection at frequencies below about 500 mcps. However, at frequencies above about 500 mcps a marked increase in current protection ratio is indicated. It is pointed out that this device was not tested in completely assembled squibs subjected to firing tests; that the device is an absorber and dissipates power; and that data obtained in this program does not permit any statement concerning use of this device for protection of a squib against accidental firing in the mode wherein the bead mix or powder may be ignited by "heat generated elsewhere and conducted to the explosive" rather than by "heat generated by currents flowing in the bridge wire itself".

4. Analytical and experimental squib ignition studies are presented in datail in Section V and Appendix D to this report. Figure 71 indicates the characteristic of the laboratory model squibs tested with bridge wire current plotted against time duration of the current. This figure is self-explanatory and defines the region of ignition, the region of no ignition, and the uncertainty. These tests constitute the basis for the adoption of a reference firing level of 0.3 amperes of bridge wire current for a time duration of 30 seconds.

C. Delay Time Effect

The effect of protective capacitance units with regard to firing circuit delay time was investigated and the results are discussed in Section VI and in Appendix E of this report. Since the delay to be expected is of the order of a microsecond the delay is considered to be negligible.

D. Assembled Squib Tests

Tests of assembled laboratory model squibs were conducted wherein it was attempted to feed sufficient power into the squib assembly to result in detonation. These tests were conducted over the 400 cps to 1100 mcps range. The technique, at each selected frequency, was to subject the squib, for 30 seconds or more at a time, to gradually increased values of line current until the minimum line current value is found which results in ignition. From results of these tests the Histograms shown in Figs. 52 and 53 were prepared. Data points were obtained as the decibel equivalent of the ratio of the line firing current to the reference level of 0.3 amperes. Up to approximately 50 mcps the signal generators used were capable of delivering sufficient power to detonate the protected squibs. Thus, the data points up to 50 mcps represent the current protection ratio to be expected from these laboratory model squibs. Above about 50 mcps the signal generators

available were generally incapable of delivering sufficient power to detonate the squibs. For this reason the histograms present a conservative picture over the higher frequency ranges and the actual protection ratio at many points is greater than that indicated.

D. Specifications

Appendix F contains a drawing depicting the laboratory model squibs tested. Appendix F also contains proposed specifications for a protective squib assembly. It is pointed out that the laboratory models tested in this program were not tested for environmental criteria as described under the portion of the specification entitled "Desired Characteristics." It is also pointed out that these laboratory model squibs have not been subjected to a test program to justify statistical statements specifying the probability of firing under certain conditions or the probability of not firing under certain conditions.

IX. CONCLUSIONS

From the analytical and experimental work performed in this program the following conclusions are drawn:

A. The concept of using capacitance elements in shunt with squib bridge wires to afford radio-frequency protection over a very wide frequency range is considered feasible. It is recognized that the use of a protected squib, in the configuration of the laboratory models tested, does not constitute an absolute guarantee against accidental detonation due to radio-frequency influence. On the other hand, it is certain that a bridge wire thus protected is less susceptible by far than an unprotected squib.

B. At frequencies below 200 KC and with currently available materials the use of the techniques explored in this program to provide insensitization does not appear practicable. Further research is required to extend the protection to this range of frequencies.

C. The laboratory models tested in this program offer the greatest degree of protection over the frequency range from 500 KC to about 10 mcps.

D. Except for a few very narrow frequency bands in the microwave region the shunt capacitance protective unit promises a minimum of 10 db of protection from 200 KC to 11 KMC.

E. Radio-frequency insensitive squibs may be fabricated from simple circuit elements and may be compactly packaged.

F. The degree of protection offered by the shunt capacitance technique may be improved, notably at frequencies below 100 mcps, by using a longer bridge wire with turns to increase its inductance and resistance. The use of a higher resistance bridge wire of course increases the DC voltage required in the intentional firing circuit.

G. The ignition delay time caused by the use of a shunt capacitance is negligible.

H. The limited nature of tests of wide band radio-frequency absorbers which were conducted in this program dictates caution in statement of conclusions. It does appear that use of a wide band RF absorber as a supplementary protective device does not offer any augmentation in current protection ratio at frequencies below about 500 mcps. It appears that use of such a supplementary device offers a material improvement in current protection ratio at frequencies above about 500 mcps. The tests performed in this program do not provide a basis for any statement pertaining to the performance to be expected if an absorber is packaged into a squib.

I. The results of this program indicate that continued research and development based on these techniques can produce simple and compact devices which will be effective for RF insensitization in a number of specific applications.

X. RAMIFICATIONS

General

This program included investigations over the frequency range from 400 cps to 11000 mcps. The data obtained and the results heretofore presented pertaining to the frequency range from about 100KC to about 800 mcps did not contain anamolies and do not require further comment.

Low Frequency Range

Reactance units employed in this program to insensitize squibs, as already indicated elsewhere, afforded little or no protection against influences having frequencies below 100 kilocycles per second. Undoubtedly, with passage of time, the state of the capacitor fabricating art will be improved, and the bounds now apparent at 100 kilocycles per second will be forced to lower frequency values. Barring an early and major breakthrough on the sector of this front of technical knowledge, however, protection to squibs at the lower frequencies, seemingly, must be obtained from means other than reactance units of the types here studied. Successful contention with certain low frequency induction field influences, by way of illustration, might follow adoption of some of the practices and devices (bifilar wound, line induction absorbing transformers; tuned traps; etc.) used by the telephone industry.

The Microwave Range

The other end of the frequency range under consideration, that is, the upper end of the ultra-high frequency section and the microwave frequency range (800.0 mc - 11,000.0 mc), an indefiniteness exists there as to the degree of protection reactance unit techniques will provide to squibs. In this realm, unlike the low frequency one just discussed, where a definite and measurable degree of protection took place, anomalous squib firings occurred in addition to the firings which provided statistical evidence of previously mentioned protection. Since the laboratory model squibs used in tests, either had technician-reworked assemblies or were technician-made, and since the number of the anomalous firings (about 10%) was somewhat in excess of that which might be ascribed to defective or faulty parts and construction, it is felt that nothing more than opinions can be offered as to causes of the abnormal firings. It is our opinion that the degree of protection to be obtained from capacitance units in the microwave region is closely related to the precision of the squib manufacturing process and the effectiveness of the quality control techniques.

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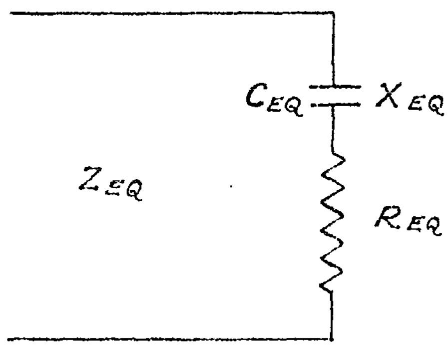
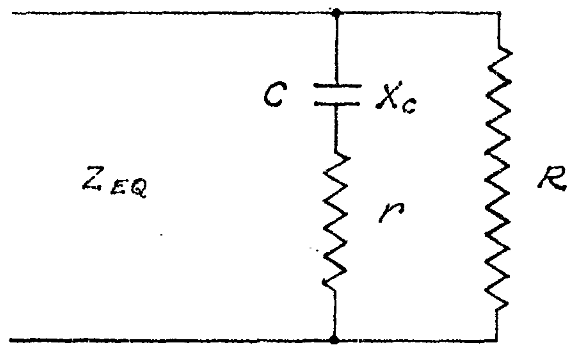
APPENDIX A

APPLICATION CONSIDERATION CONSTRAINTS

A. CORRELATION OF MEASURABLE AND THEORETICAL PARAMETERS OF A CAPACITOR.





PRACTICAL CAPACITANCE ELEMENT AS REGARDED IN INSTRUMENTATION PROCESSES.

APPROXIMATE EQUIVALENT CIRCUIT OF IMPERFECT CAPACITOR AT LOW FREQUENCIES.

LET $Z_1 = R$ AND $Z_2 = r + \frac{1}{j\omega C}$

WHERE $\omega = 2\pi f$ IS THE CIRCULAR FREQUENCY.

THEN

$$Z_{EQ} = \frac{Z_1 Z_2}{Z_1 + Z_2} = \frac{R + j\omega C r R}{1 + j\omega C(r+R)}$$

$$= \frac{R[1 + \omega^2 C^2 r(R+r)]}{1 + \omega^2 C^2 (R+r)^2} - j\,\frac{\omega C R^2}{1 + \omega^2 C^2 (R+r)^2}$$

$$R_{EQ} = \frac{R[1 + \omega^2 C^2 r(R+r)]}{1 + \omega^2 C^2 (R+r)^2}$$

$$X_{EQ} = \frac{\omega C R^2}{1 + \omega^2 C^2 (R+r)^2}$$

$$C_{EQ} = \frac{1 + \omega^2 C^2 (R+r)^2}{\omega^2 C R^2}$$

CORRELATION OF MEASURABLE AND THEORETICAL PARAMETERS OF A CAPACITOR.

WITH CONVENTIONAL MEASURING MEANS, AS BRIDGES. THERE ARE OBTAINABLE AS CHARACTERISTIC PARAMETERS OF AN IMPERFECT CAPACITOR THE FOLLOWING:

R = D-C SHUNT RESISTANCE.
C_{EQ} = APPARENT CAPACITANCE.
D = DISSIPATION FACTOR.
$= R_{EQ}/X_{EQ}$

FROM THE EXPRESSION GIVEN FOR Z_{EQ} THE DISSIPATION FACTOR CAN BE WRITTEN IN THE FORM

$$D = \frac{1 + \omega^2 C^2 r(R+r)}{\omega C R}$$

WITH THIS RELATIONSHIP AND THAT PREVIOUSLY GIVEN FOR C_{EQ}, IT IS POSSIBLE TO EFFECT A SIMULTANEOUS SOLUTION FOR THE THEORETICALLY ACTUAL CAPACITANCE C AND THE SERIES RESISTANCE r. AS THUS FOUND

$$C = \frac{1 + [D - \omega R C_{EQ}]^2}{\omega^2 R^2 C_{EQ}}$$

AND

$$r = \frac{R\{D[\omega R C_{EQ} - D] - 1\}}{1 + [\omega R C_{EQ} - D]^2}$$

B. ANALYSIS OF CAPACITIVE REACTANCE

THE EXPRESSION FOR EFFECTIVE CAPACITY REACTANCE, X_{EQ}, HAS A PEAK TYPE MAXIMUM VALUE, AS MAY BE SEEN BY DIFFERENTIATING X_{EQ} WITH RESPECT TO THE CIRCULAR FREQUENCY, ω, AND EQUATING THE DERIVATIVE TO ZERO. THAT IS

$$X_{EQ} = \frac{\omega C R^2}{1 + \omega^2 C^2 (R+r)^2}$$

$$\frac{dX_{EQ}}{d\omega} = 0 = 1 - \omega_M^2 C^2 (R+r)^2$$

WHENCE

$$\omega_M = \frac{1}{C(R+r)}$$

SUBSTITUTION OF THIS VALUE OF CIRCULAR FREQUENCY INTO THE ORIGINAL EXPRESSION FOR CAPACITIVE REACTANCE SHOWS THE REACTANCE PEAK TO AMOUNT TO

$$(X_{EQ})_{MAX} = \frac{R^2}{2(R+r)}$$

C. A CONSTRAINT UPON VALUES OF CIRCUIT PARAMETERS IN A CAPACITANCE PROTECTED SQUIB

In any alternating-current network that includes two simple paralleled branches, the one branch made up of a series-connected inductance and resistance with the second branch comprised of a similarly joined capacitance and resistance, a parallel resonant state may develop at some frequency. Occurrence of such a state would be accompanied by flow in medium and high Q circuits of a large mesh or circulating current and of a small branch-point input or line current. At such a time, then, the ratio of the latter current to the former may be less than unity.

A branch circuit pair similar to that under comment may be found in a capacitance protected squib. There the bridge wire may be made of a length such as to display, at low radio-frequencies, the qualities of conjoined inductance and resistance, while the shunting capacitance unit, being an imperfect device, is equivalent to a series combination of capacitance and resistance. Since these, as mentioned earlier, constitute the ingredients of a circuit susceptible to a resonant condition and since such a condition could prove extremely dangerous in a squib, being attended by a fractional value for the current protection ratio, a prime requirement to be imposed upon circuit element values in the case at hand is one of precluding the possibility of resonance. This may be achieved by recourse, first, to the expression for the resonant frequency of a circuit of the kind under consideration, and, second, selection of values for the independent parameters in the expression that collectively render the frequency zero or imaginary.

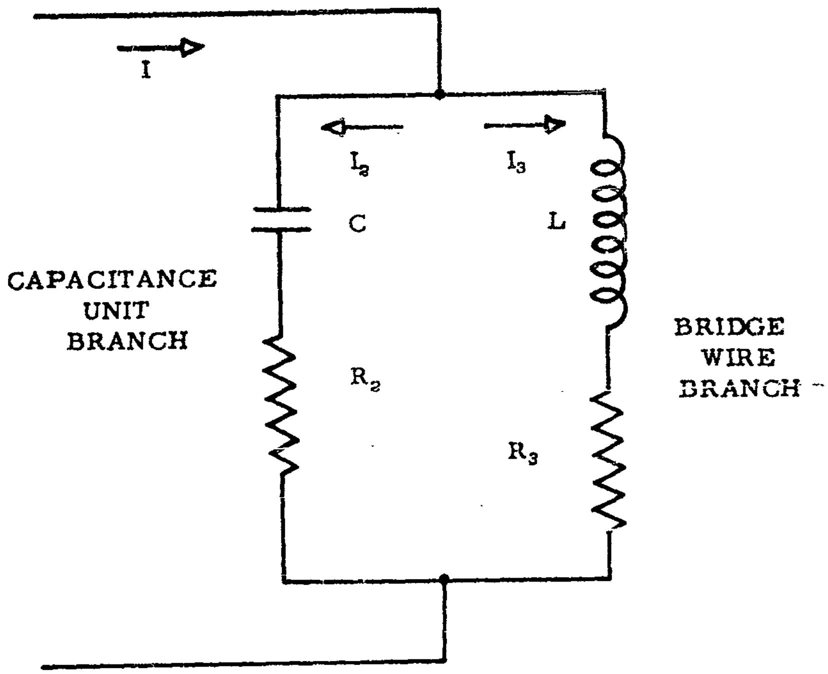
To clarify the foregoing points brief regard will be had of the circuit to which they apply, and of the appurtenant expression for resonant frequency. In the circuit which follows:

L = Inductance of the bridge wire branch (Henries).

R_3 = Resistance of the bridge wire branch (Ohms).

C = Capacity of the squib-protecting capacitance unit (Farads).

R_2 = Equivalent resistance of capacitance unit and of the wiring thereto (Ohms).



Reference to standard treatises on radio circuits, as the "Admiralty Handbook of Wireless Telegraphy" (   ), will disclose the expression for resonant frequency of the mesh diagrammed to be

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}\left[\frac{L - CR_3^2}{L - CR_2^2}\right]}$$

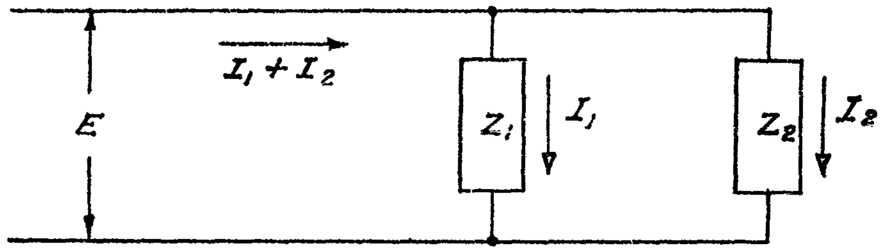
Next, terms in the bracketed part of this expression, to prevent development of a resonant condition, must be caused to have values which will make the quantity under the radical either zero or negative. In other words a design constraint is that

$$\left[\frac{L - CR_3^2}{L - CR_2^2}\right] \leqslant 0$$

APPENDIX B

DERIVATIONS PERTAINING TO MEASUREMENT TECHNIQUES

A. CURRENT PROTECTION RATIO



IN THE FOREGOING CIRCUIT, E IS THE APPLIED VOLTAGE, AND I_1 AND I_2 ARE BRANCH CURRENTS FLOWING IN IMPEDANCES

$$Z_1 = R_1 + jX_1 \quad \text{AND} \quad Z_2 = R_2 + jX_2$$

HERE R AND X DENOTE RESISTANCE AND REACTANCE, RESPECTIVELY. FURTHERMORE

$$Y_1 = \frac{1}{Z_1} = G_1 - jB_1 \quad \text{AND} \quad Y_2 = \frac{1}{Z_2} = G_2 - jB_2$$

WHERE

$$G_1 = \frac{R_1}{R_1^2 + X_1^2} \qquad G_2 = \frac{R_2}{R_2^2 + X_2^2}$$

$$B_1 = \frac{X_1}{R_1^2 + X_1^2} \qquad B_2 = \frac{X_2}{R_2^2 + X_2^2}$$

Y, G AND B DENOTE ADMITTANCE, CONDUCTANCE AND SUSCEPTANCE, RESPECTIVELY.

THE BRANCH CURRENTS HAVE VALUES

$$I_1 = EY_1 \quad \text{AND} \quad I_2 = EY_2$$

THE CURRENT PROTECTION RATIO IS

$$\left| \frac{I_1 + I_2}{I_2} \right|$$

EXPRESSED IN DECIBELS THIS RATIO BECOMES

$$N_{DB} = 20 \, LOG_{10} \left| \frac{I_1 + I_2}{I_2} \right| = 20 \, LOG_{10} \left| \frac{Y_1 + Y_2}{Y_2} \right|$$

$$= 20 \, LOG_{10} \left| \frac{(G_1 + G_2) - j(B_1 + B_2)}{G_2 - jB_2} \right|$$

WITH THE DENOMINATOR RATIONALIZED THIS EQUATION ASSUMES THE FORM

$$N_{DB} = 20 \, LOG_{10} \left| \left\{ \frac{[G_2(G_1 + G_2) + B_2(B_1 + B_2)]}{G_2^2 + B_2^2} + j \frac{[B_2(G_1 + G_2) - G_2(B_1 + B_2)]}{G_2^2 + B_2^2} \right\} \right|$$

SINCE BOTH THE CONDUCTANCE AND SUSCEPTANCE ARE FUNCTIONS OF FREQUENCY THE FOREGOING EXPRESSION WILL YIELD A NORMAL GAIN OR ATTENUATION TYPE CHARACTERISTIC.

B. POWER PROTECTION RATIO

FROM THE CIRCUIT PORTRAYAL USED FOR DERIVATION OF THE CURRENT PROTECTION RATIO IT IS ALSO POSSIBLE TO DERIVE A POWER PROTECTION RATIO. THIS FOLLOWS.

$$I_1 = EY_1 \quad \text{AND} \quad I_2 = EY_2$$

OR

$$I_1 = E(G_1 - jB_1) \quad \text{AND} \quad I_2 = E(G_2 - jB_2)$$

HERE ALL SYMBOLS HAVE THE SAME SIGNIFICANCE AS IN THE PREVIOUS DERIVATION.

CONSUMED BY EACH IMPEDANCE IS THE POWER

$$P_1 = E(EG_1) = E^2 G_1$$

AND

$$P_2 = E(EG_2) = E^2 G_2$$

THE POWER PROTECTION RATIO IS

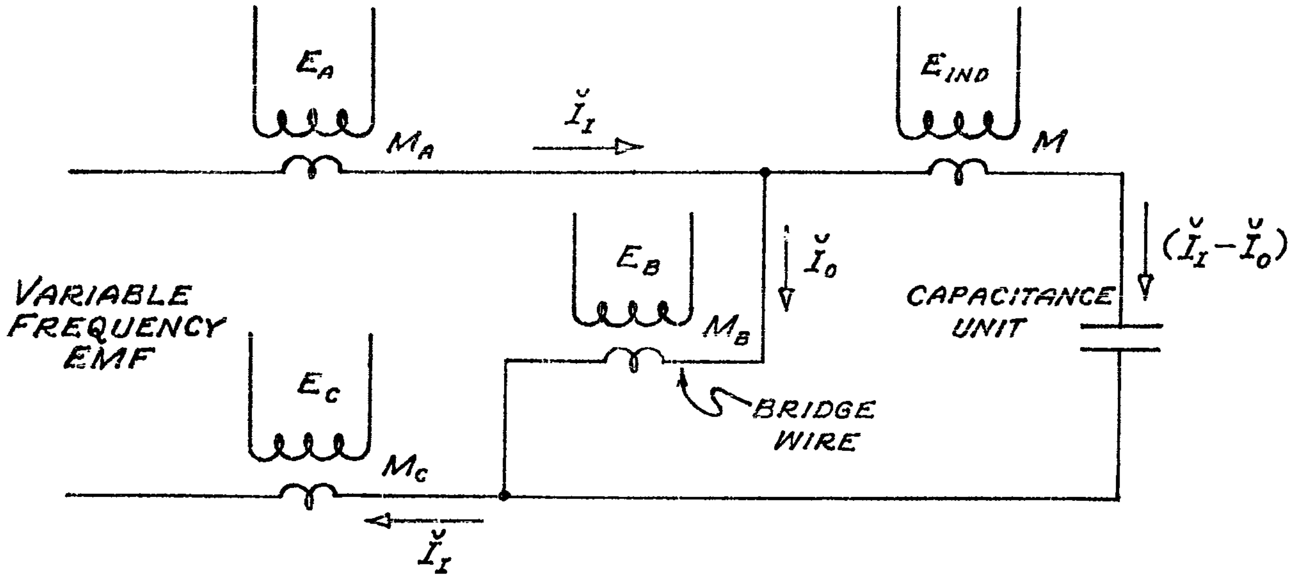
$$\frac{P_1 + P_2}{P_2} = \frac{G_1 + G_2}{G_2}$$

EXPRESSED IN DECIBELS THIS RATIO BECOMES

$$N_{DB} = 10 \ LOG_{10}\left(\frac{P_1 + P_2}{P_2}\right)$$

$$= 10 \ LOG_{10}\left(\frac{G_1 + G_2}{G_2}\right)$$

c. INDUCTIVE LOAD MEASUREMENT TECHNIQUE



IN THE FOREGOING CIRCUIT DIAGRAM

$$\check{E}_{IND} = j\omega M(\check{I}_I - \check{I}_0)$$

LET

$$\frac{|I_I|}{|I_0|} = K \qquad [N_{DB} = 20 \log_{10} K]$$

ASSUME $\check{I}_I$ AND $\check{I}_0$ TO BE IN PHASE. THEN

$$K\check{E}_{IND} = j\omega M \check{I}_I (K-1)$$

AND

$$K = \frac{j\omega M \check{I}_I}{j\omega M \check{I}_I - \check{E}_{IND}}$$

FURTHER

$$\check{I}_I = \frac{\check{E}_A}{j\omega M_A} = \frac{\check{E}_C}{j\omega M_C}$$

SUBSTITUTING THIS EXPRESSION FOR $\check{I}_I$ IN THE PRECEDING RELATIONSHIP YIELDS

$$K = \frac{\frac{M}{M_A}\check{E}_A}{\frac{M}{M_A}\check{E}_A - \check{E}_{IND}}$$

IN THE DIAGRAMS ON THE PRECEDING PAGE:

E_I AND E_0 DENOTE THE VOLTAGES INDUCED IN THE PICK-UP COILS SHOWN BY LOAD TERMINATION CURRENT I_I AND BRIDGE WIRE CURRENT I_0, RESPECTIVELY.

M_I AND M_0 SIGNIFY, RESPECTIVELY, THE MUTUAL INDUCTANCES APPLICABLE TO THE COUPLING FROM THE LOAD END OF THE TRANSMISSION LINE TO ITS PICK-UP COIL AND FROM THE BRIDGE WIRE TO ITS COIL.

THE INDUCED VOLTAGES WOULD HAVE VALUES GIVEN BY THE FOLLOWING EXPRESSIONS:

$$E_I = 2\pi f M_I I_I$$

AND

$$E_0 = 2\pi f M_0 I_0$$

WHERE f DENOTES THE FREQUENCY OF THE INDUCING CURRENTS.

FROM THESE VOLTAGE RELATIONSHIPS IT IS POSSIBLE TO WRITE THE CURRENT PROTECTION RATIO. EXPRESSED IN DECIBELS THIS IS

$$N_{DB} = 20 \log_{10} \frac{I_I}{I_0}$$

$$= 20 \log_{10} \frac{E_I M_0}{E_0 M_I}$$

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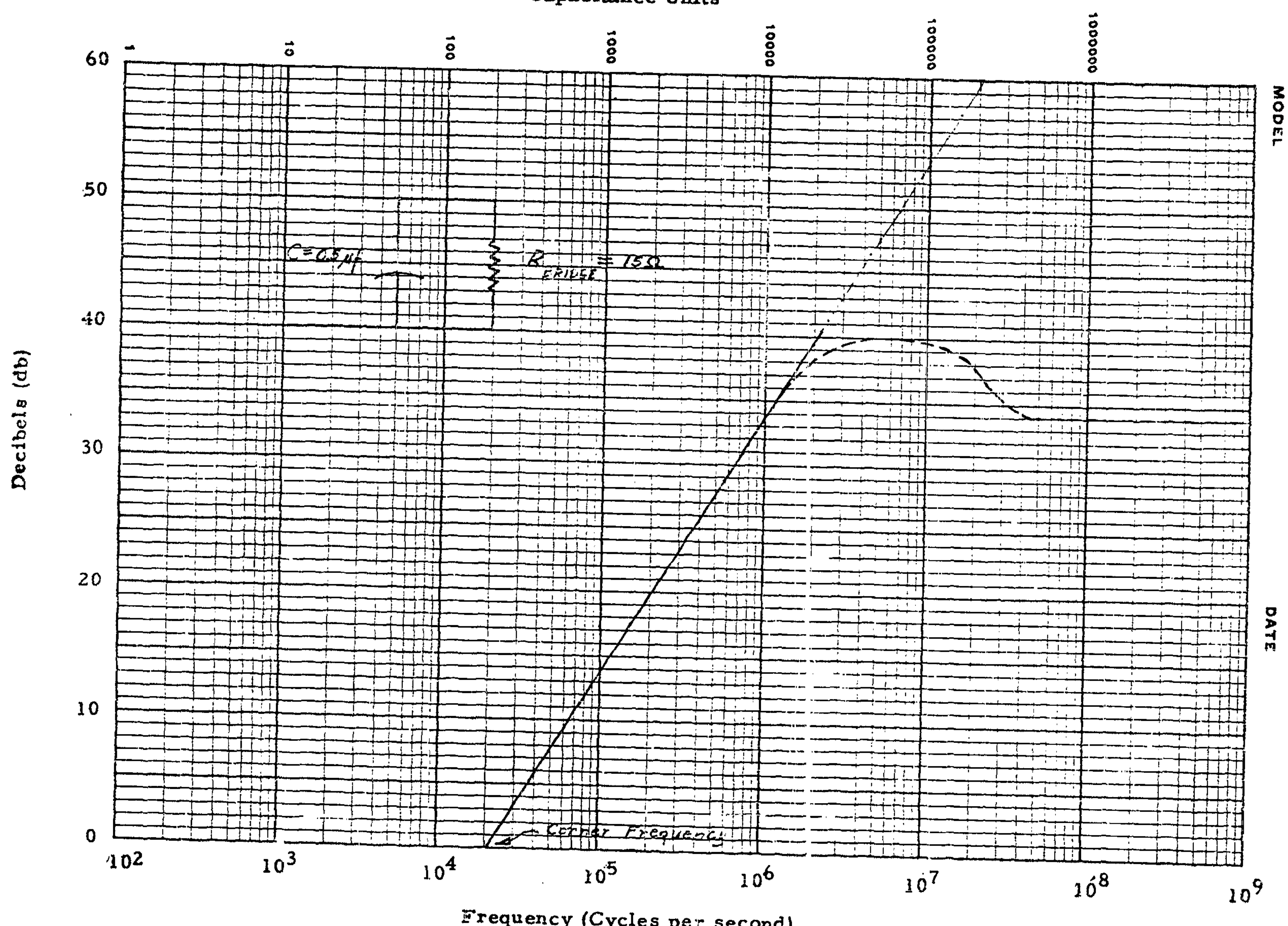
7 CYCLES X 60 DIVISIONS

Idealized Current Protection Ratio Characteristics Exhibited by Titanate Capacitance Units



APPENDIX C

DERIVATION OF AN EMPIRICAL EQUATION APPROXIMATELY ADAPTABLE TO THE TRANSFER FUNCTION RELATING TRANSMISSION LINE CURRENT TO SQUIB BRIDGE WIRE CURRENT

DERIVATION OF AN EMPIRICAL EQUATION APPROXIMATELY ADAPTABLE TO THE TRANSFER FUNCTION RELATING TRANSMISSION LINE CURRENT TO SQUIB BRIDGE WIRE CURRENT

The following transfer function derivation, which is intended to yield a function that affords only a qualitative explanation of the shape and values characteristic of experimentally determined current protection ratio curves, is based actually upon two, rather far-fetched assumptions. Stated explicitly they are as follows: (1) Over the frequency range 100.0 kc to 100.0 mc the protective capacitance unit is presumed to be representable by a simple parallel circuit one arm of which is comprised of a series connected combination of frequency and voltage invariant capacitive, resistive, and inductive elements, while the second arm is made up of a purely resistive element; and (2) the squib bridge wire, throughout the 100.0 kc to 100.0 mc frequency range, is supposed to behave as a fixed resistance. Utilizing these assumptions one may depict a squib that is insensitized, through capacitance means, to radio-frequency influences by a diagram such as that which follows. In that diagram letters alongside circuit element symbols have the below-given significations:

C - Capacity exhibited by the electrically imperfect, squib protecting capacitor (Farads).

L - Self-inductance inherent in the squib protecting capacitor and its connecting leads (Henries).

R - Resistance of the squib bridge wire (Ohms).

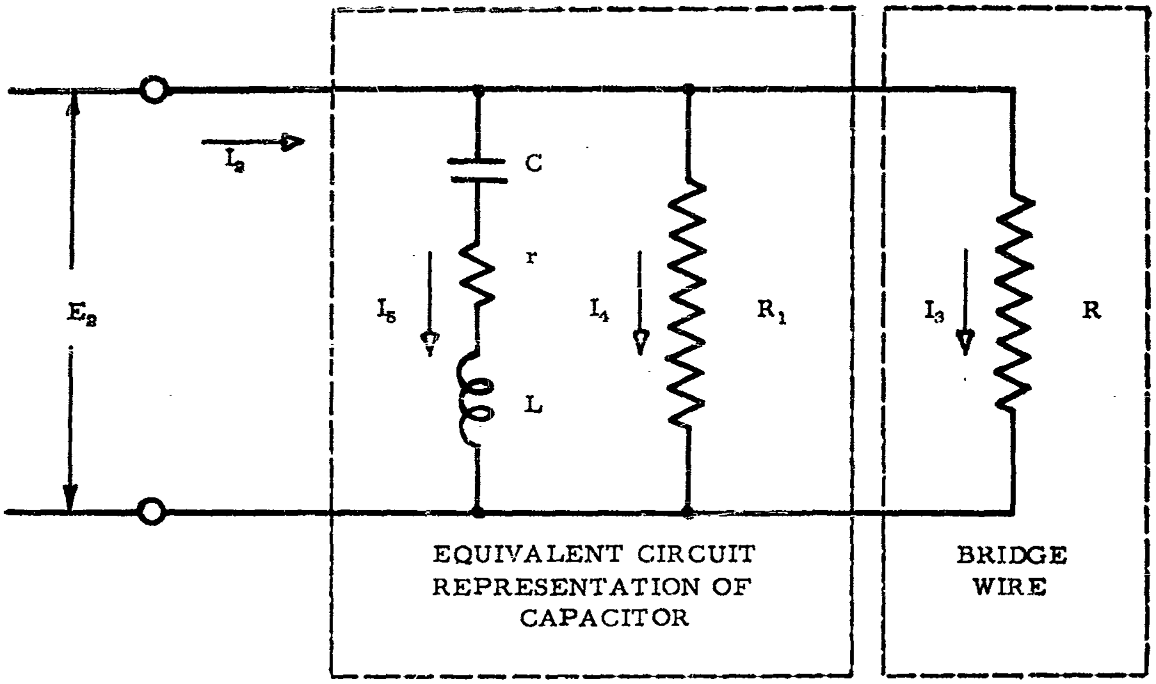
R_1 - Resistance in the equivalent circuit representation of a capacitance unit which is denotative of the unit leakage (Ohms).

r - Resistance in the equivalent circuit representation of a capacitance unit which resistance is denotative of power consumption in the capacitor and inductor elements (Ohms).

E_2 - Potential difference between terminals of the squib (Volts).

I_2 - Transmission line current at squib terminals (Amperes).

I_3, I_4, I_5 - Currents flowing, respectively, through branch circuits 3, 4, and 5 of the squib (Amperes).



EQUIVALENT CIRCUIT FORM OF PROTECTED SQUIB AT VERY HIGH FREQUENCIES

Nodal analysis of the foregoing circuit leads to the two equations

$$I_2 = E_2 \left\{ \frac{Cp}{LCp^2 + Crp + 1} + \frac{1}{R_1} + \frac{1}{R} \right\}$$

and

$$I_3 = \frac{E_2}{R}$$

The first equation of this pair may be recast into the form

$$I_2 = E_2 \left[\frac{R_1 + R}{R_1 R} \right] \left\{ \frac{LCp^2 + C\left[r + \frac{R_1 R}{R_1 + R} \right] p + 1}{LCp^2 + Crp + 1} \right\}$$

By taking the ratio of I_2, as just represented, to I_3, the current protection ratio for the squib is obtained. Thus

$$\frac{I_2}{I_3} = \left[\frac{R_1 + R}{R_1} \right] \left\{ \frac{LCp^2 + C\left[r + \frac{R_1 R}{R_1 + R} \right] p + 1}{LCp^2 + Crp + 1} \right\}$$

Since steady-state conditions only are being considered here the factor $p = j\omega$, where ω denotes the circular frequency, $2\pi f$, and j the imaginary operator $\sqrt{-1}$.

For plotting purposes the current protection ratio is expressed in decibels, in other words, ordinates of included curves are actually

$$\text{DECIBELS} = 20 \log_{10} \frac{I_2}{I_3}$$

At moderately low frequencies (below 100.0 kc) the effect of inductance L is negligible and the capacitor leakage resistance, R_1, ordinarily is quite large relative to the bridge wire resistance, R. If these facts are translated into the extreme premises $L = 0$ and $R_1 = \infty$, the current protection ratio expression just derived simplifies to the relationship

$$\frac{I_2}{I_3} = \left\{ \frac{C(r + R)p + 1}{Crp + 1} \right\}$$

A still further simplification of the current protection ratio expression may be made by supposing the capacitor to be a perfect device. In such case it would have no losses and the resistance term, r, would equal zero. If this were so the ratio indicated as applicable to low frequencies would degenerate to

$$\frac{I_2}{I_3} = \left[CRp + 1 \right]$$

Obvious from this last relationship is the initial form of current protection ratio curves. That form, if the curves are plotted on log paper, as is ordinarily done, would be characterized by a + 6.0 decibel per octave slope. Curves given herein and based upon experimentally obtained data include, for reference purposes, + 6.0 decibel per octave asymptotes. Moreover, each of these is shown to start from a corner frequency defined by the time constant CR. This parameter, while very convenient, will be seen to be too small, the deficiency leading to a slight displacement of the asymptote from the straight portion of the curve wherewith it appears. Essential coincidence of asymptote and curve over a short range of frequencies could be obtained, of course, if the more nearly correct time constant, C (r + R), were used to determine the corner frequency.

APPENDIX D

DERIVATION OF AN APPROXIMATE EXPRESSION FOR THE TRANSIENT HEATING OF A SQUIB BRIDGE WIRE WHEN TRAVERSED BY A CONSTANT CURRENT

DERIVATION OF AN APPROXIMATE EXPRESSION FOR THE TRANSIENT HEATING OF A SQUIB BRIDGE WIRE WHEN TRAVERSED BY A CONSTANT CURRENT

As a first step toward fulfilling provisions 4.5.1, 4.5.2 and 4.5.3 of Exhibit "A" to Purchase Request No. 36922, these treating of ignition characteristics of laboratory model squibs, the accompanying derivation was carried out. It is based, within bounds dictated by practical engineering considerations, upon the applicable physical principles governing electrical production of heat, heat absorption, and heat transfer. Main bounds in the case constrain differential equations used to be of linear form; most parameters to be invariant with wide temperature changes; and an idealized temperature condition to prevail just outside the bridge wire surface.

Justification for an analysis such as is presented here follows essentially from a regard of the factors that affect temperature states both in and about squib bridge wires, and from the adequacy of the data secured through this analysis. Generally speaking, bridge wires are so disposed that heat developed in them flows both longitudinally along the wires and normally thereto; into bodies whose thermal conductivities may be quite high or very low. All such heat movements, of course, owe their being specifically to support of bridge wires by relatively large leads; to spot coatings on the bridge wires themselves of bead or flash mixes; and to contact on the part of wires with explosive powder particles, with insulated supports, and with air. Since it is practically out of the question to make due allowances for the effects of all of these factors, and since the results of the approximate analysis carried out are of the correct order of magnitude, any efforts expended on a more thorough treatment of the matter, in large part, would be wasted. Furthermore, it must be borne in mind that use of the relationship deduced is made for design purposes only after its essential correctness has been confirmed, beyond any reasonable doubt, by experimental data.

In the derivation under comment symbols employed and the denotations thereof are as follows:

α = Temperature coefficient of resistivity of bridge wire (0.0001667/$^\circ$ C for Tophet "A" wire - 80% Ni, 20% Cr)

A = Surface area of bridge wire (Square centimeters)

H = Outer or exterior heat conductivity. (Newton's Law of Cooling). (Gram-calories/square centimeter-second-$^{\circ}$C) (Approximately 0.0108 for 3.1 mil diameter Tophet "A" wire).

I = Constant current (Amperes).

K = Thermal conductivity of substance adjoining bridge wire. (Gram-calories/centimeter-second-$^{\circ}$C). (Approximately 0.000060 for air).

M = Mass of bridge wire (Grams).

R_0 = Bridge wire resistance at 20° C. (Ohms).

S = Specific heat of bridge wire (Gram-calories/gram-$^{\circ}$C). (Approximately 0.104 for Tophet "A" wire).

T = Instantaneous temperature ($^{\circ}$ C).

T_0 = Initial temperature ($^{\circ}$ C).

t = Instantaneous time (Seconds).

0.2388 = Conversion factor (Joules to gram-calories).

Now the power consumed by the bridge wire heats both the wire and the surrounding substances. This fact is expressed mathematically as follows:

$$0.2388\ I^3 R_0 \left[1 + \alpha (T - T_0)\right] = Ms \frac{dT}{dt} + KA \frac{dT}{dn}$$

In this the left-hand term denotes the rate of development of Joulean heat; the first of the right-hand terms gives the rate of assumption of heat by the bridge wire; and the second of the right-hand terms gives the heat flowing normally from the bridge wire surface into adjoining substances.

Next, the assumption is made that the heat flow normal to the surface of a bridge wire per unit of time is dependent upon a temperature gradient directly proportional to the wire surface temperature. This supposition implies, of course, that heat absorption by substances contiguous to the wire is negligible. Symbolically, this relationship becomes

$$K \frac{dT}{dn} + H(T - T_0) = 0$$

A brief discourse on this particular boundary condition is given in the treatise "Conduction of Heat in Solids" by H. S. Carslaw and J. C. Jaeger (   ).

Substitution of this relationship in the original equation after making a sign change to provide for outward flow of heat gives

$$0.2388\, I^2 R_0 \left[1 + \alpha (T - T_0) \right] = Ms \frac{dT}{dt} + HA(T - T_0)$$

Rearrangement of terms on a compatible basis yields the equation

$$\frac{dT}{dt} + \left[\frac{HA - 0.2388\, I^2 R_0 \alpha}{Ms} \right] T = \left[\frac{0.2388\, I^2 R_0 (1 - \alpha T_0) + HAT_0}{Ms} \right]$$

Following a Laplace transformation this passes into the form

$$T(p) = \frac{\left[\frac{0.2388\, I^3 R_0 (1 - \alpha T_0) + HAT_0}{Ms} \right]}{p \left\{ p + \left[\frac{HA - 0.2388\, I^2 R_0 \alpha}{Ms} \right] \right\}} + \frac{T_0}{\left\{ p + \left[\frac{HA - 0.2388\, I^2 R_0 \alpha}{Ms} \right] \right\}}$$

An inverse transformation of this expression gives a solution for the temperature in real time. In one convenient form the temperature relation is

$$T = \left[\frac{0.2388 I^2 R_0}{HA - 0.2388 I^2 R_0 \alpha}\right] \left\{1 - \varepsilon^{-\left[\frac{HA - 0.2388 I^2 R_0 \alpha}{Ms}\right] t}\right\} + T_0$$

The expression just derived for the instantaneous temperature, T, of a bridge wire may be rearranged so that the time, in seconds, in which this temperature is reached becomes the dependent variable. That is

$$t = -\left[\frac{Ms}{HA - 0.2388 I^2 R_0 \alpha}\right] \log_\varepsilon \left\{1 - \left[\frac{HA - 0.2388 I^2 R_0 \alpha}{0.2388 I^2 R_0}\right](T - T_0)\right\}$$

APPENDIX E

APPROXIMATE MATHEMATICAL ANALYSIS OF SQUIB IGNITION DELAY CAUSED BY PROTECTIVE CAPACITANCE UNITS

APPROXIMATE MATHEMATICAL ANALYSIS OF SQUIB IGNITION DELAY CAUSED BY PROTECTIVE CAPACITANCE UNITS

In the analysis which follows it is assumed that the protected squib assembly is energized from a constant voltage, direct current source over a transmission line whose length is sufficiently short to permit of its being represented by a single, "T" circuit section. Such a combination of devices together with a circuit closing and opening means is diagrammed below. There the letters associated with circuit element symbols have the below-given meanings:

C - Capacity of squib protecting capacitor (Farads).

C_L - Capacity of the entire transmission line in lumped form (Farads).

E - Voltage of the energizing source (Volts).

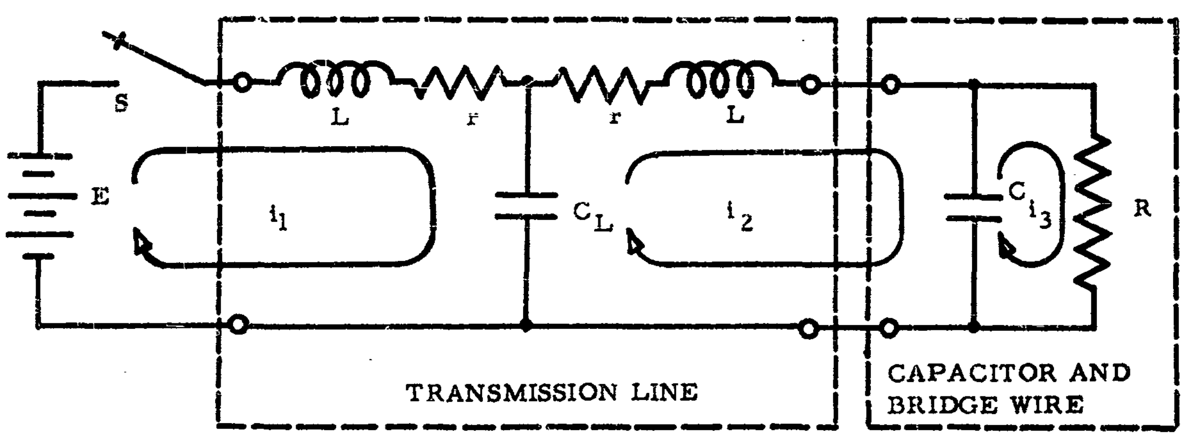
i_1, i_2, i_3 - Currents identified with meshes 1, 2, and 3, respectively (Amperes).

L - Self-inductance between either end of the transmission line and its midpoint (Henries).

r - Resistance between either end of the transmission line and its midpoint (Ohms).

R - Resistance of the bridge wire (Ohms).

S - Switch.



PROTECTED SQUIB CIRCUIT REPRESENTATION

Objectives of this analysis may be realized most readily by proceeding from the voltage drop equations associated with the three meshes shown in the foregoing circuit representation.

Thus there is associated with the first mesh the equation:

$$r\,i_1 + L\,p\,i_1 + \frac{i_1}{p\,C_L} - \frac{i_2}{p\,C_L} = E$$

With the second and third meshes there are associated, similarly, the equations

$$\frac{i_1}{p\,C_L} - r\,i_2 - L\,p\,i_2 - \frac{i_2}{p\,C_L} - \frac{i_2}{p\,C} + \frac{i_3}{p\,C} = 0$$

and

$$\frac{i_2}{p\,C} - R\,i_3 - \frac{i_3}{p\,C} = 0$$

Cast into matrix form these three equations give

$$\begin{bmatrix} \left(r + L\,p + \frac{1}{p\,C_L}\right) & -\frac{1}{p\,C_L} & 0 \\ \frac{1}{p\,C_L} & -\left(r + L\,p + \frac{1}{p\,C_L} + \frac{1}{p\,C}\right) & \frac{1}{p\,C} \\ 0 & \frac{1}{pC} & -\left(R + \frac{1}{p\,C}\right) \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} = \begin{bmatrix} E \\ 0 \\ 0 \end{bmatrix}$$

In the relationships just presented the letter p denotes the mathematical operator d/dt, that is, the symbolism which indicates a first derivative with respect to time is to be taken of some succeeding parameter.

Since bridge wire heating ensues from flow through it of current i_3, this term must be solved for next. Such solution, set out as the quotient of a division of one determinant by another, is

$$i_3 = \frac{\begin{vmatrix} \left(r + Lp + \dfrac{1}{pC_L}\right) & -\dfrac{1}{pC_L} & E \\ \dfrac{1}{pC_L} & -\left(r + Lp + \dfrac{1}{pC_L} + \dfrac{1}{pC}\right) & 0 \\ 0 & \dfrac{1}{pC} & 0 \end{vmatrix}}{\begin{vmatrix} \left(r + Lp + \dfrac{1}{pC_L}\right) & -\dfrac{1}{pC_L} & 0 \\ \dfrac{1}{pC_L} & -\left(r + Lp + \dfrac{1}{pC_L} + \dfrac{1}{pC}\right) & \dfrac{1}{pC} \\ 0 & \dfrac{1}{pC} & -\left(R + \dfrac{1}{pC}\right) \end{vmatrix}}$$

The determinant representing the dividend in this case reduces to the quantity

$$\frac{E}{C\ C_L\ p^2},$$

whereas the determinant denoting the divisor may be written

$$\Delta = \frac{1}{C C_L p^3} \left\{ C C_L R L^2 p^4 + C_L L (2 C r R + L) p^3 + \left[2 C L R + C_L L (R + 2 r) + C C_L r^2 R \right] p^2 + \left[2 (L + C r R) + C_L r (R + r) \right] p + (R + 2 r) \right\}$$

As before, of course,

$$i_3 = \frac{\dfrac{E}{C C_L p^3}}{\Delta}$$

An expression in the time domain for current i_3 may be found readily now from the foregoing dividend and divisor expressions by effecting appropriate Laplace transformations of them; factoring the resulting polynomials; and, finally, performing either inverse transformations or contour integrations of the ensuing polynominal factors. Since this would lead in the general case to a lengthy and unwieldy equation, one of doubtful practical value, the actual work involved will not be undertaken here. Instead a specific example wherein certain simplifications are made is provided to illustrate the steps outlined.

Illustrative Example

The expression in the preceding development last given for current i_s, in normal form, would be a fourth order, linear differential equation with constant coefficients. To obtain the solution of such an equation, generally, would entail finding the roots of a quartic. If, however, the simplifying assumption is made in this illustrative example that the transmission line joining the squib to a power source has negligible inductance, the roots of only a quadratic equation need be found. Advantage of this fact is taken in what follows.

System parameters, next, will be supposed to have the below-given values:

> Squib bridge wire resistance, $R = 15.0$ Ohms.
> Squib shunt capacity, $C = 0.5 \times 10^{-6}$ Farad.
> Transmission line resistance (total), $2r = 0.170$ Ohm.
> Transmission line capacity (total), $C_L = 0.003 \times 10^{-6}$ Farad.
> Transmission line inductance (assumed), $L = 0$ Henry.
> Source voltage, $E = 24.0$ Volts.

Numerical values of parameters being used herein are very nearly those associated with laboratory model squibs and with a one hundred-foot length of type RG8A/U, coaxial transmission line.

Substitution, now, of the numerical values for the corresponding parameters in the expression developed for Δ gives for the extant terms

$$
\begin{aligned}
C C_L r^2 R &= 1.626 \times 10^{-16} \\
2 C r R &= 1.275 \times 10^{-6} \\
C_L r (R + r) &= 3.84 \times 10^{-9} \\
(R + 2r) &= 15.17
\end{aligned}
$$

and for $\Delta C C_L p^2$,

$$1.626 \times 10^{-16} p^2 + 1.279 \times 10^{-6} p + 15.17$$

Upon factoring this becomes

$$15.17 \left[(1 + 1.273 \times 10^{-10} p) \ (1 + 841.0 \times 10^{-10} p) \right]$$

If, now, the quotient $E / \Delta C C_L p^3$ is set up, there is obtained the following, separated operator form of differential equation for current i_3

$$i_3 = \frac{24.0}{15.17 \left[(1 + 1.273 \times 10^{-10} p) \ (1 + 841.0 \times 10^{-10} p) \right]}$$

A Laplace transformation of this expression, the transformation taking into account the fact that the source voltage requires treatment as a step function, yields

$$i_3 (S) = \frac{1.582}{S \left[(1 + 1.273 \times 10^{-10} S) \ (1 + 841.0 \times 10^{-10} S) \right]}$$

Here S is the conventional Laplace transform parameter.

The foregoing function belongs to a class identified by the structure

$$\frac{1}{S \, (1 + T_1 S) \, (1 + T_2 S)} ,$$

and this class has as inverse transform

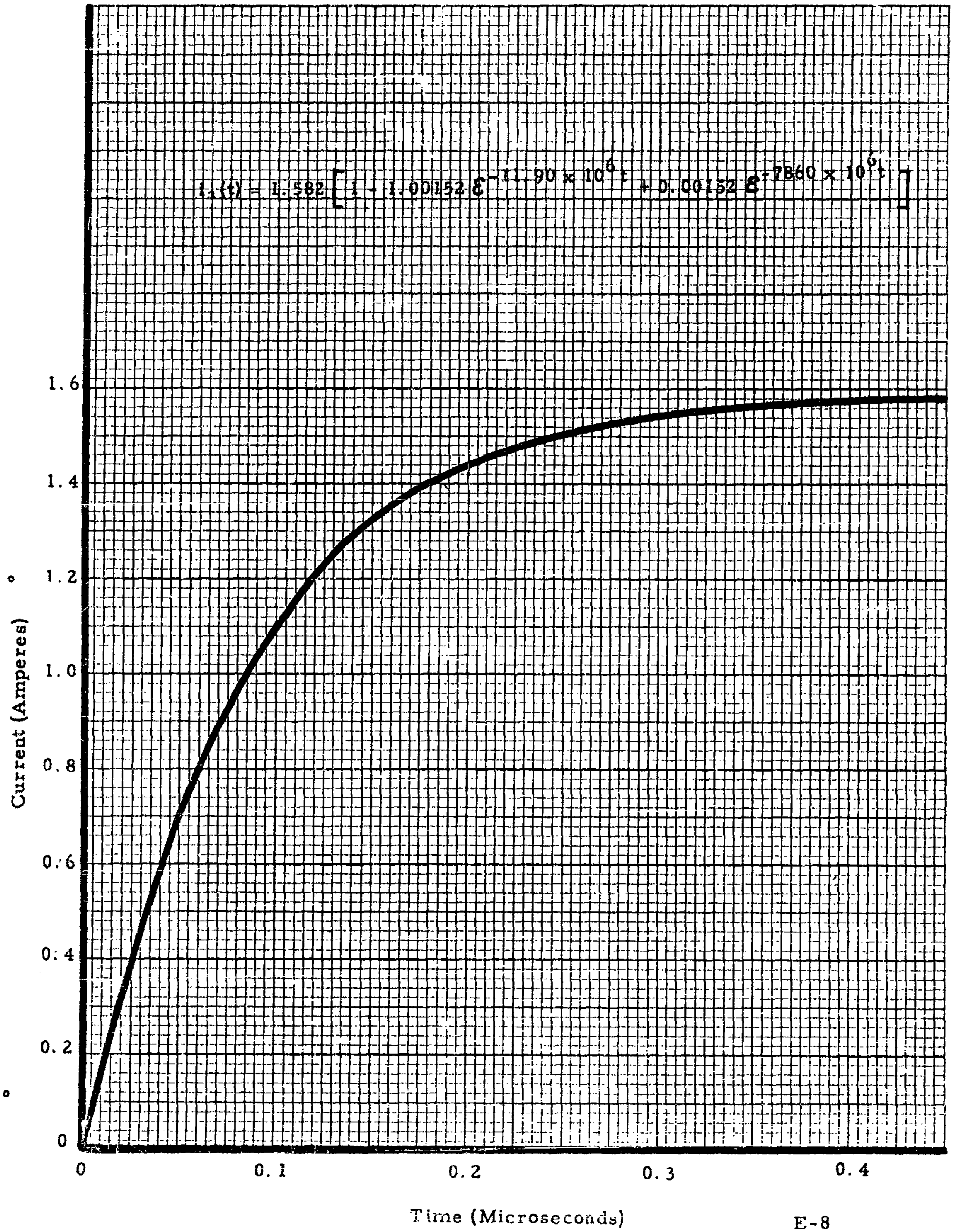
$$1 + \frac{1}{(T_2 - T_1)} \left[T_1 \, \varepsilon^{-t/T_1} - T_2 \, \varepsilon^{-t/T_2} \right]$$

It follows, finally, that the value of current i_3 is given by

$$i_3(t) = 1.582 \left[1 - 1.00152\, \mathcal{E}^{-11.90 \times 10^6 t} + 0.00152\, \mathcal{E}^{-7860 \times 10^6 t} \right]$$

A graphical portrayal of this equation is provided on an accompanying sheet.

Graphical Representation of Squib Ignition Delay
Caused by Protective Capacitance Units



Illustrative Example

Use will be made in this case of the whole expression developed for the bridge wire current i_3. In other words all the parameters associated with a representative transmission line will be taken into account, and the effects of all in defining the transient phenomena will be left to appear. As here determined, then, current i_3 will show forth essentially the same behavior as is observable in an actual situation.

Except for the line inductance, which here is given its appropriate finite value, all other system parameters will have the same values as were assigned to them in the preceding example. Thus:

Squib bridge wire resistance, $R = 15.0$ Ohms.
Squib shunt capacity, $C = 0.5 \times 10^{-6}$ Farad.
Transmission line resistance (total), $2r = 0.170$ Ohm.
Transmission line capacity (total), $C_L = 0.003 \times 10^{-6}$ Farad.
Transmission line inductance (total), $2L = 16.22 \times 10^{-6}$ Henry.
Source voltage, $E = 24.0$ Volts.

Substitution, now, of the numerical values for the corresponding parameters in the expression developed for Δ gives for the extant terms

$$C C_L R L^2 = 1.485 \times 10^{-24}$$
$$C_L L(2CrR + L) = 2.29 \times 10^{-19}$$
$$2CLR = 1.215 \times 10^{-10}$$
$$C_L L(R + 2r) = 3.54 \times 10^{-13}$$
$$C C_L r^2 R = 1.626 \times 10^{-16}$$
$$2(L + CrR) = 1.75 \times 10^{-5}$$
$$C_L r(R + r) = 3.84 \times 10^{-9}$$
$$(R + 2r) = 15.17$$

whereupon $\Delta C C_L p^2$ becomes

$$1.485 \times 10^{-24} p^4 + 2.29 \times 10^{-19} p^3 + 1.219 \times 10^{-10} p^2$$
$$+ 1.75 \times 10^{-5} p + 15.17$$

This may be factored and represented as the product of two, normalized quadratic expressions. Additionally, the quadratic expressions may be written in the form used conventionally to show the coefficient of the independent variable where appearing to the first power to be the quotient of twice a damping factor by the natural circular frequency, and the coefficient of this variable where shown raised to the second power to be the reciprocal of the square of the natural circular frequency. Set up in this last mentioned way the quartic reads

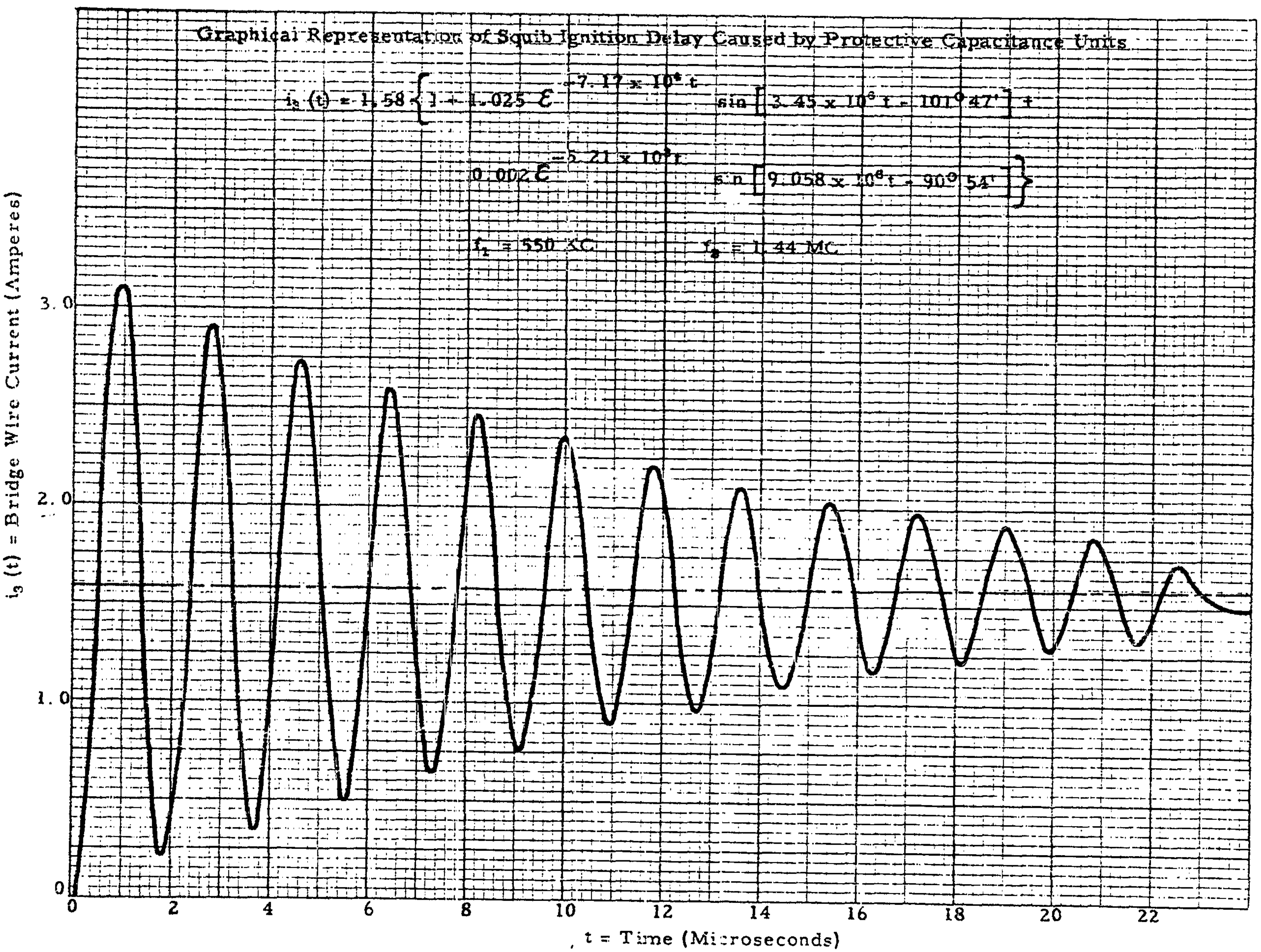
$$15.17 \left\{ \left[1 + \frac{(2)(0.235)}{0.3526 \times 10^{6}} p + \frac{1}{(0.3526 \times 10^{6})^{2}} p^{2} \right] \left[1 + \frac{(2)(0.000575)}{9.058 \times 10^{6}} p + \frac{1}{(9.058 \times 10^{6})^{2}} p^{2} \right] \right\}$$

If, now, the quotient $E/\Delta C C_L p^2$ is set up, the current i_3 will be given as 1.582 divided by the foregoing quadratic term product within the opposed braces. A Laplace transformation of such an expression for i_3, the transformation again taking into account the fact that the source voltage requires treatment as a step function and that boundary conditions entering into the subsidiary equation are all zero, will give a solution for the bridge wire current in the S or complex frequency domain. Proceeding from this into the real time domain, through an inverse transformation, leads to the following relationship

$$i_3(t) = 1.58 \left\{ 1.0 + 1.025\, \mathcal{E}^{-7.17 \times 10^{4} t} \sin\left[3.45 \times 10^{6} t - 101^{\circ} 47'\right] + 0.002\, \mathcal{E}^{-5.21 \times 10^{3} t} \sin\left[9.058 \times 10^{6} t - 90^{\circ} 54'\right] \right\}$$

Oscillatory terms in this equation indicate that the bridge wire current has two alternating components in its make-up, one with a frequency of 550 kc and the second with 1.44 mc.

From the graphical portrayal of current i_3, plotted on an accompanying sheet, it may be seen that this quantity attains its steady-state value in less than 0. 50 microsecond, oscillating about this value for several cycles thereafter. Since the root-mean-square value of the composite current is evidently quite close to the steady-state value after 0. 50 microsecond it seems reasonable to suppose that the retardation of current build-up due to inclusion in squibs of protective capacitance units is negligible.


Graphical Representation of Squib Ignition Delay Caused by Protective Capacitance Units
$i_3(t) = 1.58 \left\{ 1 + 1.025\, \mathcal{E}^{-7.17 \times 10^6 t} \sin\left[3.45 \times 10^6 t - 101^\circ 47'\right] + 0.002\, \mathcal{E}^{-5.21 \times 10^6 t} \sin\left[9.058 \times 10^6 t - 90^\circ 54'\right] \right\}$
f_1 = 550 KC
f_2 = 1.44 MC
i_3 (t) = Bridge Wire Current (Amperes)
t = Time (Microseconds)
0
1.0
2.0
3.0
0
2
4
6
8
10
12
14
16
18
20
22

APPENDIX F

SPECIFICATIONS FOR SQUIB ASSEMBLY

SPECIFICATIONS FOR SQUIB ASSEMBLY

A. Specifications For Titanate Capacitance Units

These specifications are definitive of titanite capacitance units as illustrated in Details 8 and 9, Photo 12, having particular applicability to electro-explosive initiators. The specification provisions prescribe unit characteristics and properties which are currently believed to be essential to units in the application stated. Primarily the units are intended to render the initiators insensitive to wideband radio-frequency power introduced into the initiator transmission lines, by means of inherent current by-passing and power reflecting capabilities. Secondarily, the specifications prescribe desirable qualities to be possessed by units so as to fulfill spatial, environmental and operational conditions.

1.0 Physical

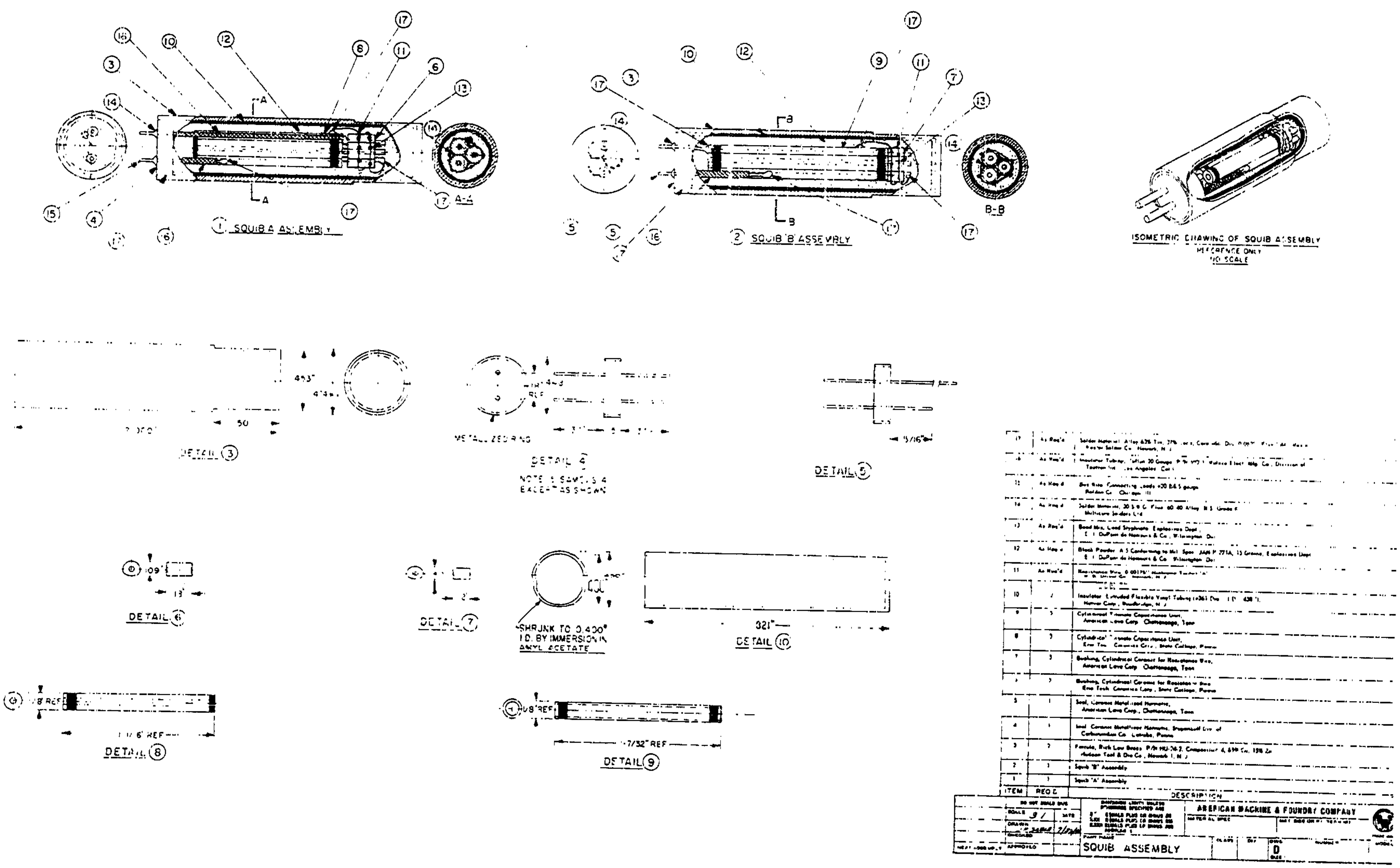
1.1 The capacitance units ultimately shall have a hollow cylindrical form and shall be as small as specification conditions render practicable. Dimensions which are not to be exceeded are a length of 1-1/4 inches and an outside diameter of 3/8 inch. Both external and internal surfaces shall be provided with electrically conductive coatings to which metallic conductors may be readily soldered.

2.0 Electrical

2.1 The capacity of any unit in a given lot shall not be less than 0.25 microfarad when measurements of this parameter are made at 25°C and with a 1.0 volt (RMS) test signal whose frequency is 1000 cps.

2.2 Functional variations of the capacity with the voltage impressed upon the unit and with frequency shall be permissible, but no decline of the capacity below 0.25 microfarad shall occur for voltages ranging from zero to 60.0 volts D-C or peak A-C) nor for frequencies below 10.0 megacycles Above 10.0 megacycles the capacity may fall off with frequency but any such decline shall not render the capacity lower than that which would result if it were an inverse function of frequency.

2.3 The D-C resistance of capacitance units at 25°C shall not be less than 0.75 megohm while a D-C emf of 30.0 volts is impressed upon them, nor less than 0.50 megohm while subjected to a similar potential difference of 60.0 volts. Furthermore, the D-C resistance as measured from one electrode of the unit to the second shall not differ more than 25% from the resistance found by interchange of the electrode order, that is, effecting measurements



Photograph 12.

from the second electrode to the first.

2.4 The capacitance units, while retaining the characteristic properties previously specified, shall not exhibit series resonance phenomena nor a preponderance of inductive reactance when subjected to low amplitude A-C voltages (19.0 volts RMS and less) whose frequencies may range from 400 cps to 5.0 megacycles.

2.5 The capacitance units shall not exhibit permanent characteristic changes nor dielectric breakdown while stressed for a minimum period of one minute by alternating potential differences having an RMS value of at least 75.0 volts and a frequency of 1000 cps.

2.6 No marked change in any electrical characteristics of capacitance units shall occur as a result of subjection to temperatures ranging from -65°F to +165°F. A marked change here shall be understood to be one wherein the value of a characteristic parameter changes more than 50% from its nominal value. Also, units shall be capable of accepting without impairment of operational capacity and physical properties a thermal shock defined by a temperature change extending from -65°F to +165°F, or vice versa, and having a duration of five minutes.

3.0 Materials

3.1 Materials that are nutrients of fungi shall not be included in the structure of capacitance units if use of such materials may be practically circumvented.

3.2 Critical and strategic materials shall not be included in fabrication of capacitance units unless use thereof is absolutely necessary.

3.3 Materials to be included in capacitance units shall be of such nature and be so processed that stability of electrical characteristics of units would be preserved in circumstances involving unit storage for five years at temperatures ranging from +20°F to +90°F and which are accompanied by relative humidities up to 50%.

3.4 Materials conjoined to form the bodies of capacitance units should be selected, in part if practicable, with a view to imparting high thermal capacities to bodies.

4.0 Producibility. Capacitance units shall be producible with available production facilities and by conventional methods.

B. FERRULE. The ferrule, as shown in Detail 3, Photo 12, is made of rich low brass, its composition being 85% Cu and 15% Zn. Wall thickness is 0.013 inches.

C. SEAL: The seal, as shown in Detail 4, Photo 12, is of ceramic material with a solderable metallized surface bonded to the circumference for hermetic sealing of the device. Leads are AWG #20 tinned copper buss wire.

D. INSULATOR: The insulator, as shown in Detail 10, Photo 12, is of extruded vinyl tubing shrunk to proper size by immersion in amyl acetate.

E. BUSHING The bridge wire bushing, as shown in Details 6 and 7, Photo 12, is made of ceramic material.

F. Desirable Characteristics

1.0 Operating Characteristics

1.1 The electroexplosive device, including the initiator or initiators, shall be immune to the heat effects produced in the housing or protective device (as determined) by circulating currents induced by prolonged exposure to the electromagnetic environment. Inherent losses in the protective device must be adequately dissipated to avoid "cook off" of the initiator.

1.2 The electroexplosive device, including the initiator or initiators, shall be highly insusceptible to currents produced by induction and/or conduction in connecting leads of various lengths

1.3 The radio frequency protective or isolating method or device shall include protection against static charge, transients, and noise modulated, pulse modulated and continuous wave radio frequency radiation.

1.4 The electroexplosive device must be designed so that:

1.4.1 All will operate when subjected to a direct current of one ampere magnitude for 10 milliseconds.

1.4.2 None will operate when subjected to a direct current of 500 milliamperes magnitude for 10 milliseconds.

1.4.3 None will operate when subjected to a direct current of 100 milliamperes magnitude for two (2) hours.

1.4.4 The sensitivity of the device will not be changed after being subjected to a direct current of 100 milliamperes magnitude for two (2) hours.

1.4.5 The D-C resistance of the squib bridge wire shall not exceed a value where its ruggedness is impaired or jeopardized.

1.4.6 The electroexplosive device shall be capable of being operated from a 28-volt, low impedance source.

2.0 Environmental Conditions: If vibration isolators or other auxiliary devices are needed to enable the assembly to meet the requirements of this specification, such devices shall be considered as integral parts of the assembly. The packaged assembly shall be designed to function as specified under the conditions defined in "Operating Environment" after subjection to conditions defined in "Non Operating Environment".

2.1 Operating Environment

2.1.1 LINEAR ACCELERATIONS: The device shall be capable of operating under the following Linear Accelerations:

2.1.1.1 Longitudinal acceleration of 100g in the forward direction and 75g in the aft direction, for a duration of one minute in each direction.

2.1.1.2 Lateral Acceleration of 40g in any direction for a duration of one minute.

2.1.2 SHOCK: The device shall be capable of operating under longitudinal shocks of 100g in the fore and aft direction for a period of five (5) milliseconds and under lateral shocks of 40g for a duration of five (5) milliseconds.

2.1.3 VIBRATION: The following criteria shall apply: .036 inch double amplitude from 5 to 75 cycles per second. Constant 10g from 75 cycles per second to 2000 cycles per second. The frequency shall vary uniformly from 5 to 75 cycles per second and return in from 10 to 15 minutes. The device shall be vibrated for one hour between each of the limits specified. In the event that resonant points are found, the device shall be vibrated at the resonant point for one hour. In the event that more than one resonant point is found, the hour shall be equally divided between resonant points.

2.1.4 TEMPERATURE: The device shall be capable of operation immediately after exposure for eight hours to temperatures of $-65^{\circ}F$ and $+165^{\circ}F$.

2.1.5 ALTITUDE. The device shall be capable of operation at all altitudes from sea level to 100,000 feet. It is desired that the device be capable of operation at all altitudes from sea level to 500,000 feet.

2.1.6 THERMAL SHOCK: The device shall be capable of operation immediately after exposure to thermal shock of $-65^{\circ}F$ to $+165^{\circ}F$ in five minutes.

2.1.7 ACOUSTICS: The device shall be capable of operating during and immediately after the following acoustic environment:

OCTAVE BAND (cps)	BAND ACOUSTIC PRESSURE LEVEL (Decibels re $2x10^{-4}$dynes/cm^2)
37.5 to 75	120
75 to 150	125
150 to 300	129
300 to 600	134
600 to 1200	132
1200 to 2400	123
2400 to 4800	114
4800 to 9600	102
overall	140

2.2 Non Operating Environment

2.2.1 Storage Conditions:

2.2.1.1 CONTROLLED STORAGE: Storage for five years at temperatures ranging from $+20^{\circ}F$ to $+90^{\circ}F$ and at relative humidities of less than 50% shall not degrade the reliability and operating characteristics of this device.

2.2.1.2 UNCONTROLLED STORAGE. The device shall be capable of operating after withstanding a six-month exposure to the following environments without degradation of reliability or operating characteristics.

2.2.1.2.1 Temperatures ranging from $-80^{\circ}F$ to $+160^{\circ}F$. Moisture conditions may consist of relative humidities ranging from 30 to 100 per cent and/or condensation between -80F and +75F and relative humidities decreasing linearly from 30 per cent at +85F to approximately 5 per cent at +160F.

2.2.1.2.2 Rainfall of approximately four inches per hour for a two hour period.

2.2.1.2.3 Exposure and storage conditions generally encountered on a wharf adjacent to a large body of salt water.

2.2.1.2.4 Conditions encountered in desert atmospheres containing sand and dust particles.

2.2.1.2.5 Tropical atmosphere containing fungus spores.

2.2.1.2.6 Impact shocks of 600g applied in all directions, individually, with each shock to reach a maximum in 0.5 milliseconds and with a minimum duration of 2 milliseconds.

2.2.1.2.7 Exposure to radiant energy equivalent to 30 days natural exposure to sunlight.

2.3 General Specifications for Environmental Testing, Aeronautical and Associated Equipment (MIL-E-5272A) shall be a requirement insofar as it is applicable and not in conflict with this statement of work.

3. PROBABILITIES

3.1 DUD: The probability that the device will fail to operate properly, after the appropriate igniting signal is received, shall be less than one (1) in ten thousand.

3.2 PREMATURE:

3.2.1 The probability that the device will spontaneously ignite, with no signal present, shall be less than one (1) in one million.

3.2.2 The probability shall be less than one (1) in one hundred thousand that the device will prematurely ignite, due to the influence of electromagnetic energy throughout the frequency spectrum specified herein, when the currents induced in the leads are not more than 10 db above a reference firing current. The referenced firing current is defined as that value of DC current which, when allowed to flow through the bridge wire for 1 minute will reliably fire the squib.

3.2.3 The probability that the device will ignite when subjected to a direct current of 100 milliamperes or less shall be less than one (1) in ten thousand.

3.3 COUNTERMEASURES: All practical measures shall be taken to insure the immunity of the device to countermeasures of all types.

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2	National Aeronautics and Space Administration, ATTN: Space Task Group, (Mr. Joseph Dodson), Langley AFB, Va
3	American Machine & Foundry Company, Alexandria Division, ATTN: Mr. John F. Johnson, 1025 North Royal Street, Alexandria, Va
1	Battelle Memorial Institute, 505 King Avenue, Columbus, Ohio
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Air Force Special Weapons Center,
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STUDY AND TESTING OF RADIO FREQUENCY INSENSITIVE ELECTROEXPLOSIVE MATCHES (SQUIBS), by American Machine & Foundry Company, October 1961, 242 pages incl illus. (Project 5791) (AFSWC-TR-61-88)
UNCLASSIFIED Report

The USAF is endeavoring to significantly reduce the hazards associated with the inadvertent initiation of electroexplosive devices by electromagnetic fields.
A small attenuator or filter with high insertion loss and/or mismatch characteristics, preferably integral with the electroexplosive device, is considered the device which would best satisfy the existing and projected needs and objectives of the Air Force.
High-dielectric constant capacitance units used as a shunt across squib bridgewires are thoroughly investigated over a frequency range of approximately 100 kilocycles to 10,500 megacycles. The results of laboratory work and theoretical considerations are suitably reported. The feasibility of
(over)

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1. Bridge wires
2. Capacitors
3. Ceramics
4. Electromagnetic radiation
5. Heat transfer
6. Premature probability
7. Radio-frequency attenuators
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9. Squibs

I. American Machine and Foundry Co., Alexandria Va.
II. Contract AF 29(601)-2769
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